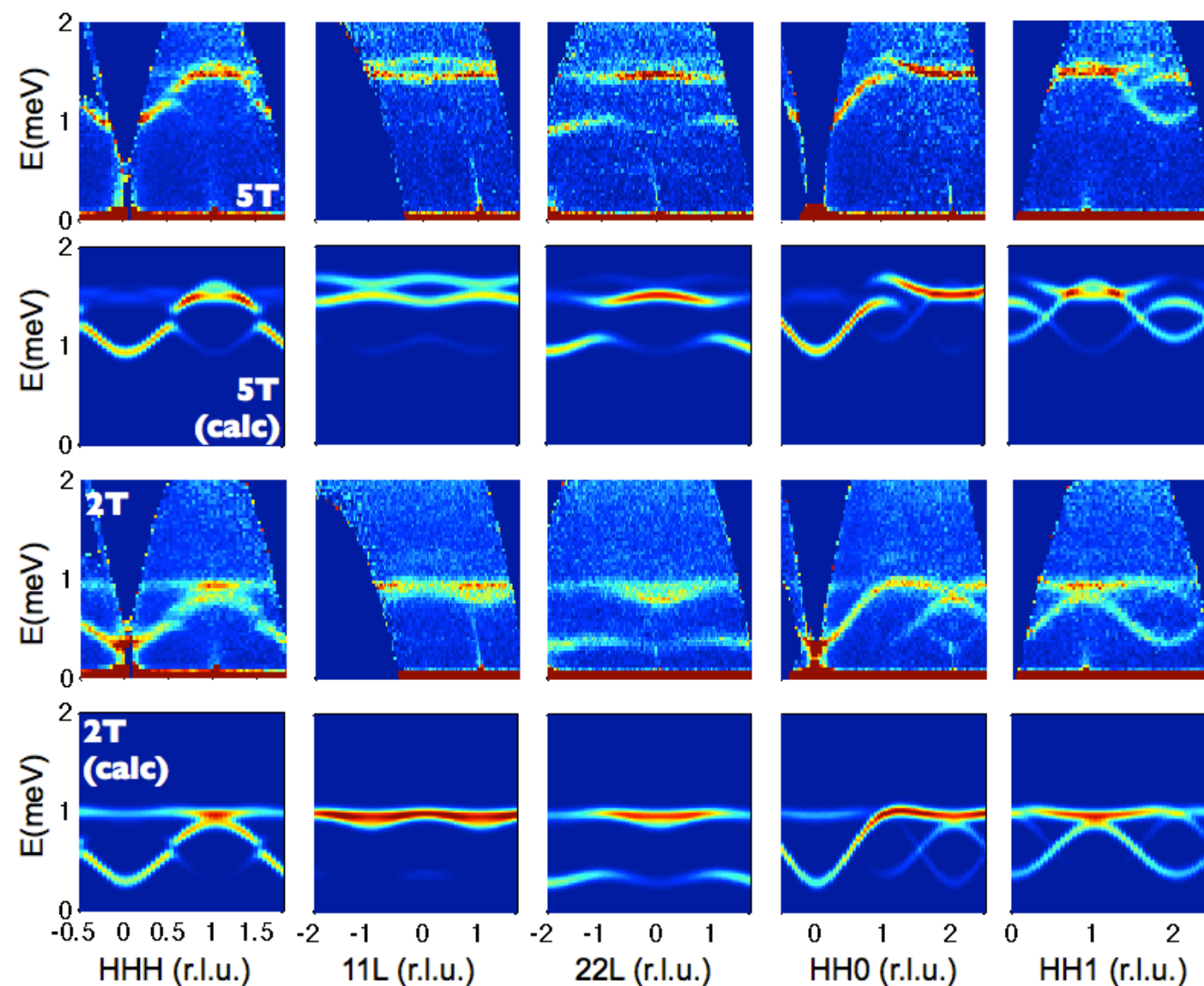


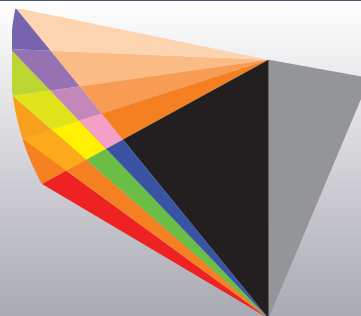
# Frustrated Magnetism as Seen Through the Lens of DCS

K.A. Ross <sup>1,2</sup>  
K. Fritsch <sup>1,3</sup>  
E. Kermarrec <sup>1,4</sup>  
J. Gaudet <sup>1</sup>  
A. Hallas <sup>1</sup>  
J.P. Clancy <sup>1,5</sup>  
J.P.C. Ruff <sup>1,6</sup>  
S. Haravifard <sup>1,7</sup>  
J. Wagman <sup>1</sup>  
M.M.P. Couchman <sup>1</sup>  
H.A. Dabkowska <sup>1</sup>  
L. Savary <sup>8,9</sup>  
L. Balents <sup>8</sup>



<sup>1</sup> McMaster University  
<sup>2</sup> Colorado State University  
<sup>3</sup> HZB  
<sup>4</sup> U Paris Sud (Orsay)  
<sup>5</sup> University of Toronto  
<sup>6</sup> CHESS, Cornell University  
<sup>7</sup> Duke University  
<sup>8</sup> KITP, UC Santa Barbara  
<sup>9</sup> MIT

**Bruce D. Gaulin**  
McMaster University



**Brockhouse Institute**  
for **Materials Research**



# John and Bill at McMaster

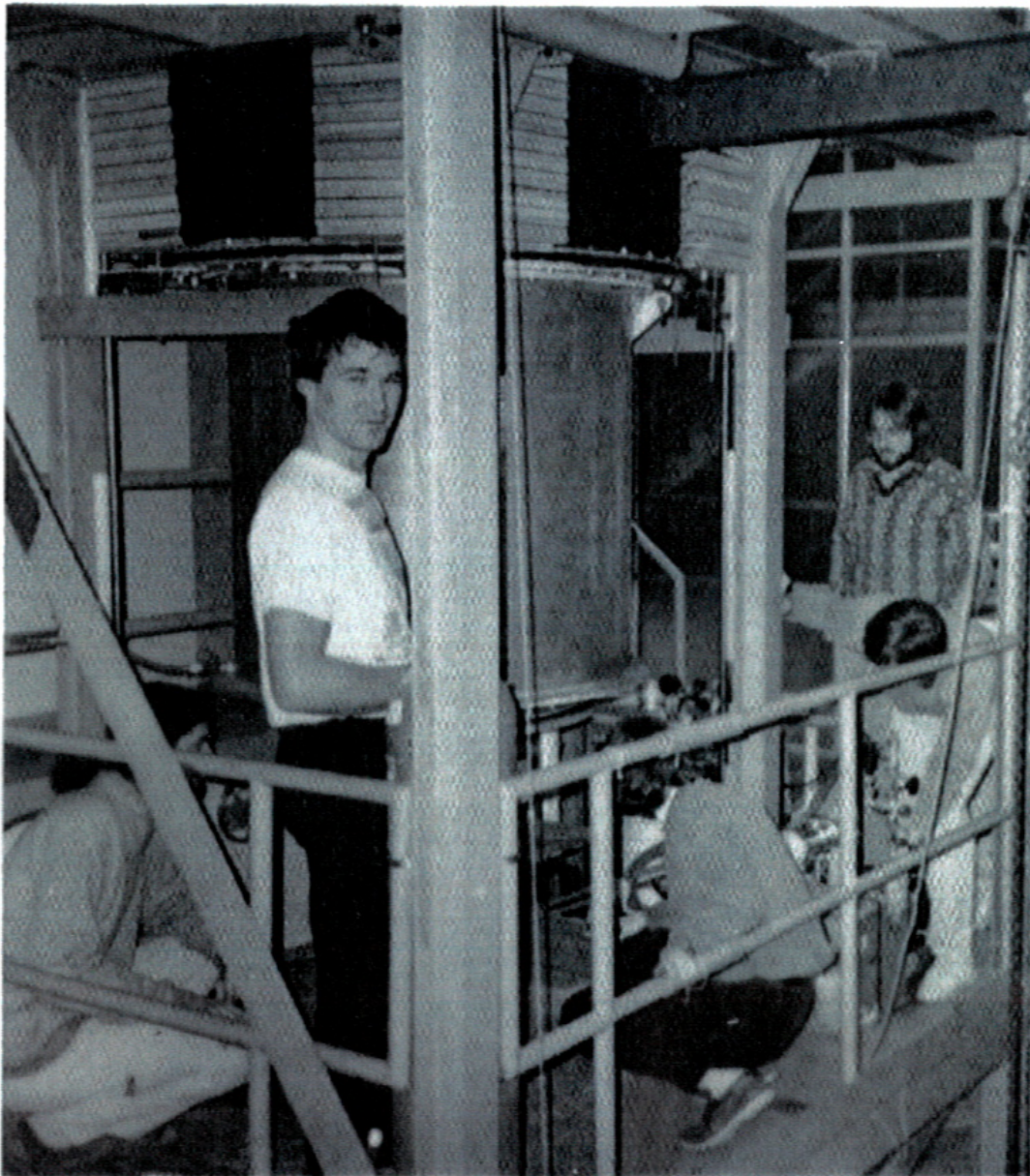


Harmonic and Anharmonic Vibrations in Rubidium Metal  
John Richard Dawn Copley PhD 1970

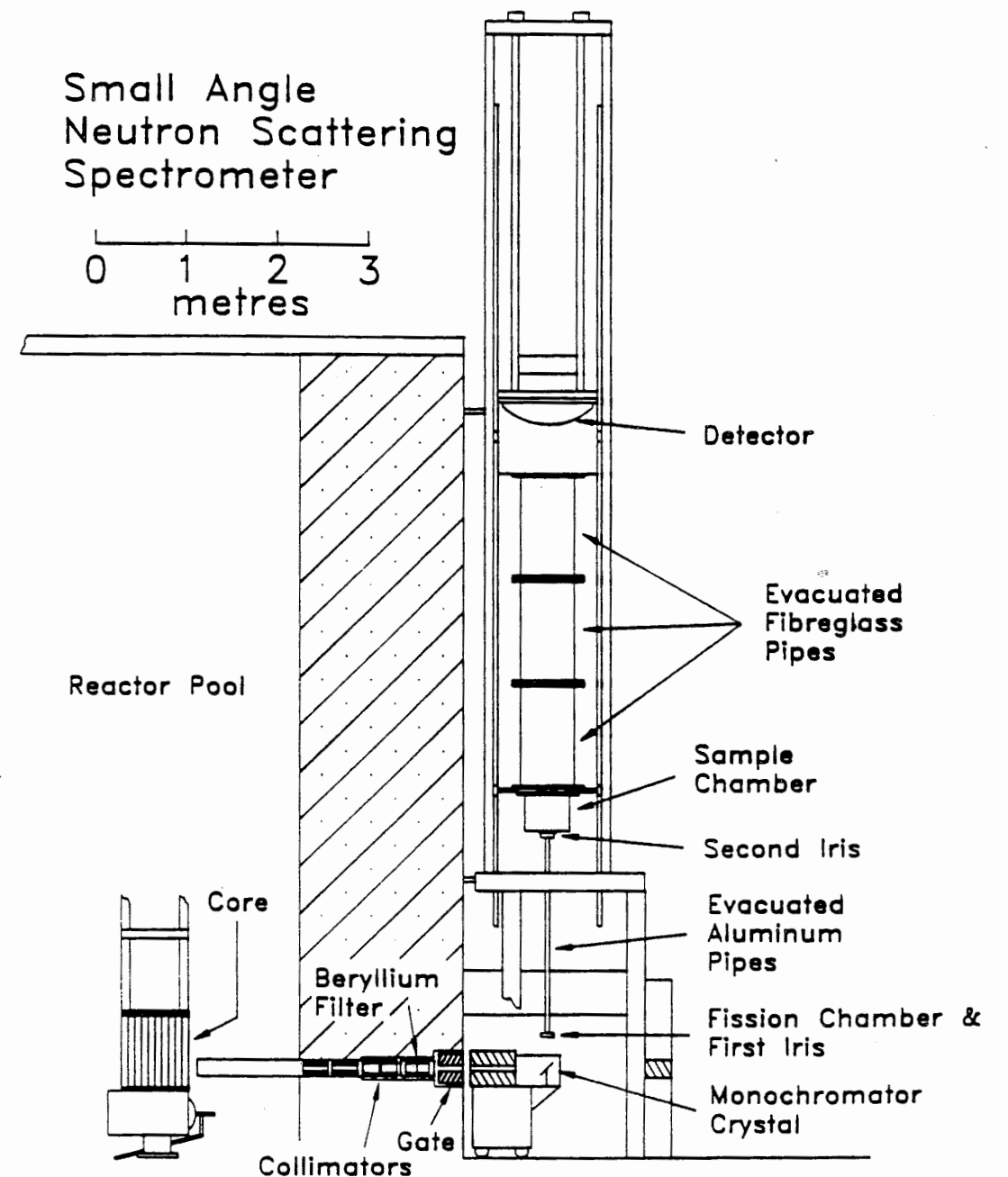
Neutron Scattering Studies of the Dynamics of Imperfect Crystals  
William Atsushi Kamitakahara PhD 1972



# John's SANS I at the McMaster Nuclear Reactor

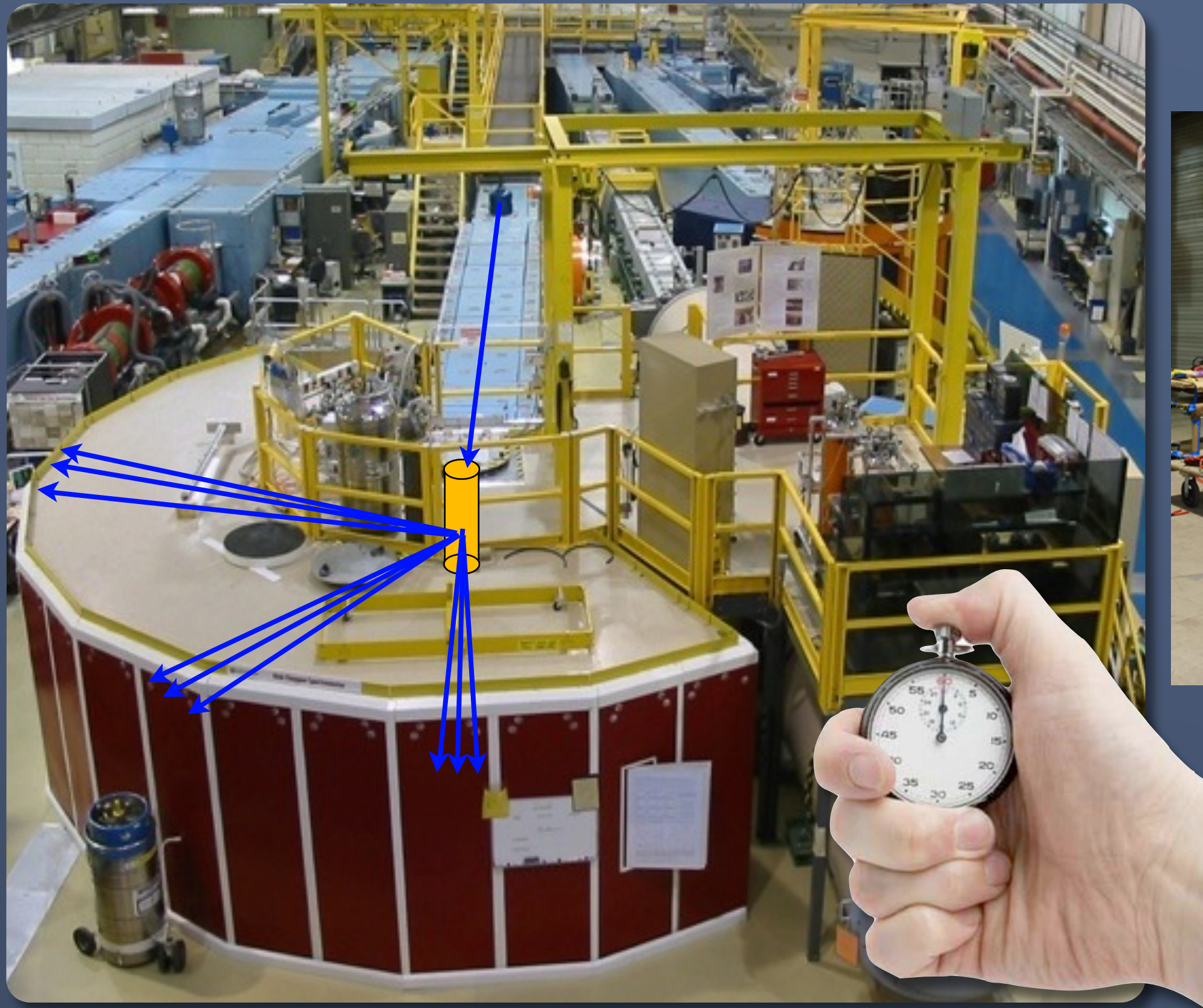


*Part of the neutron scattering group, (from left to right) Thom Mason, Andrew Harrison, Sarah Penny, Professor Gaulin and Jan Reimers, working around the Small Angle Neutron Scattering (SANS) spectrometer at the McMaster Reactor.*



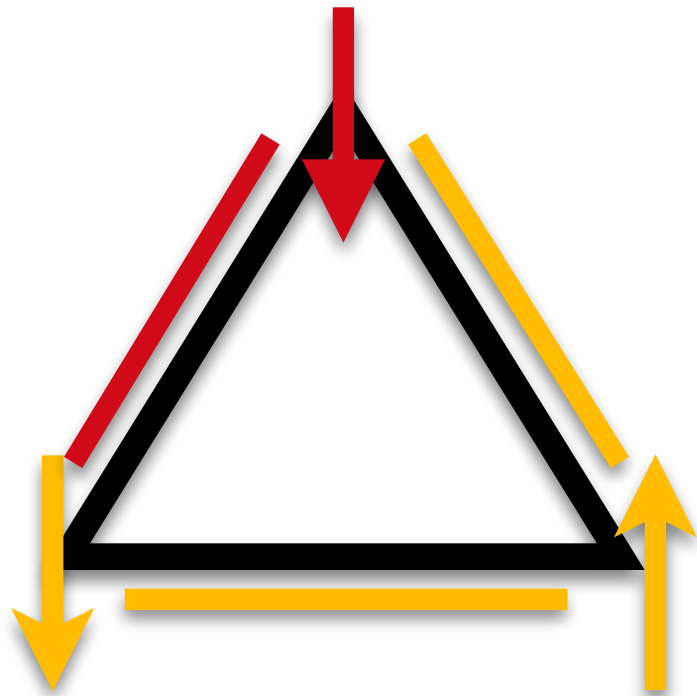


# Time of Flight Neutron Scattering at DCS

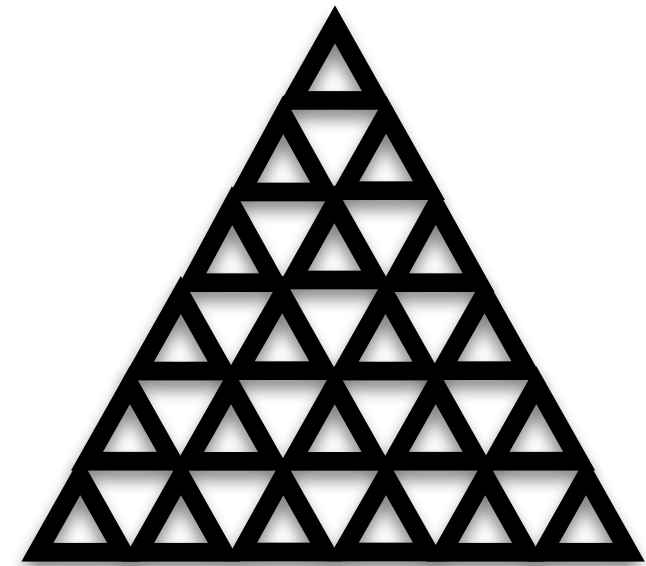




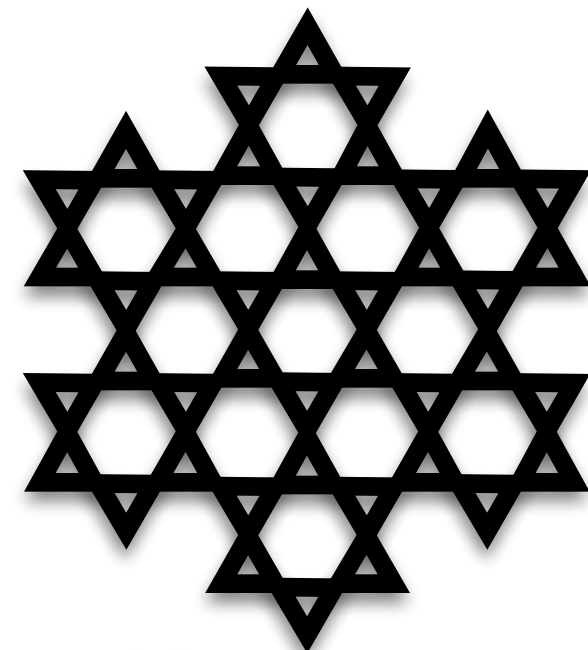
# Geometric Frustration in 2D



prefer  $\uparrow \downarrow$  alignment,  
but choice of 3rd spin  
direction is unclear



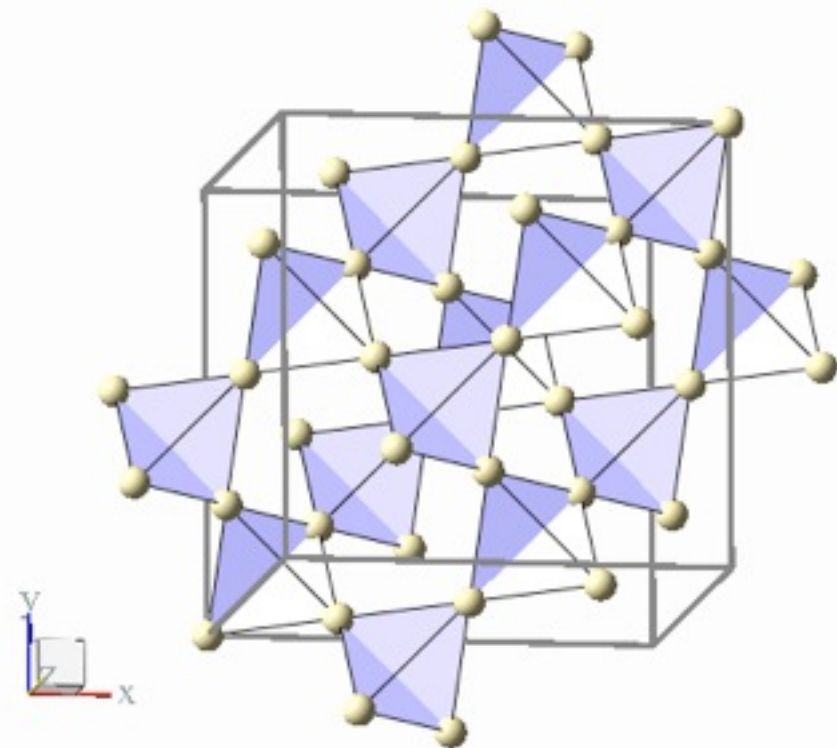
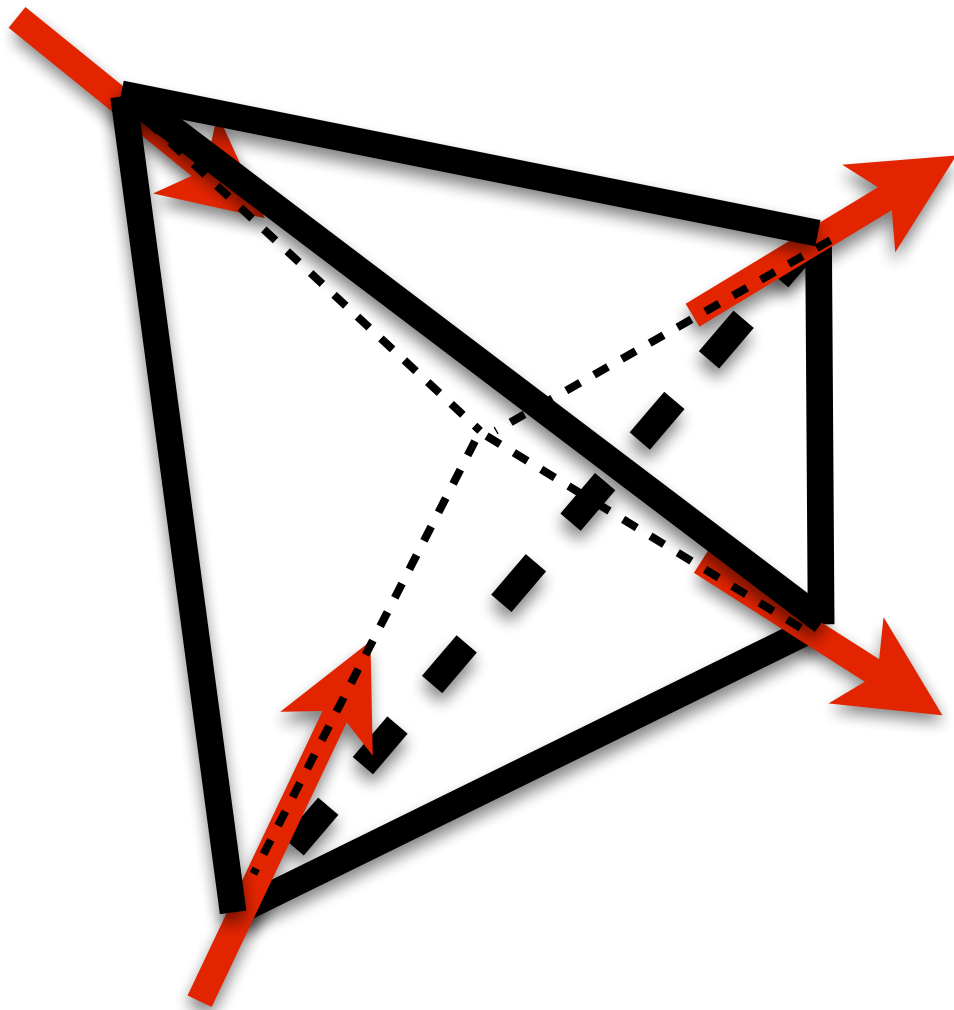
Triangular



Kagome



# Spin Ice Physics on Tetrahedra in 3D

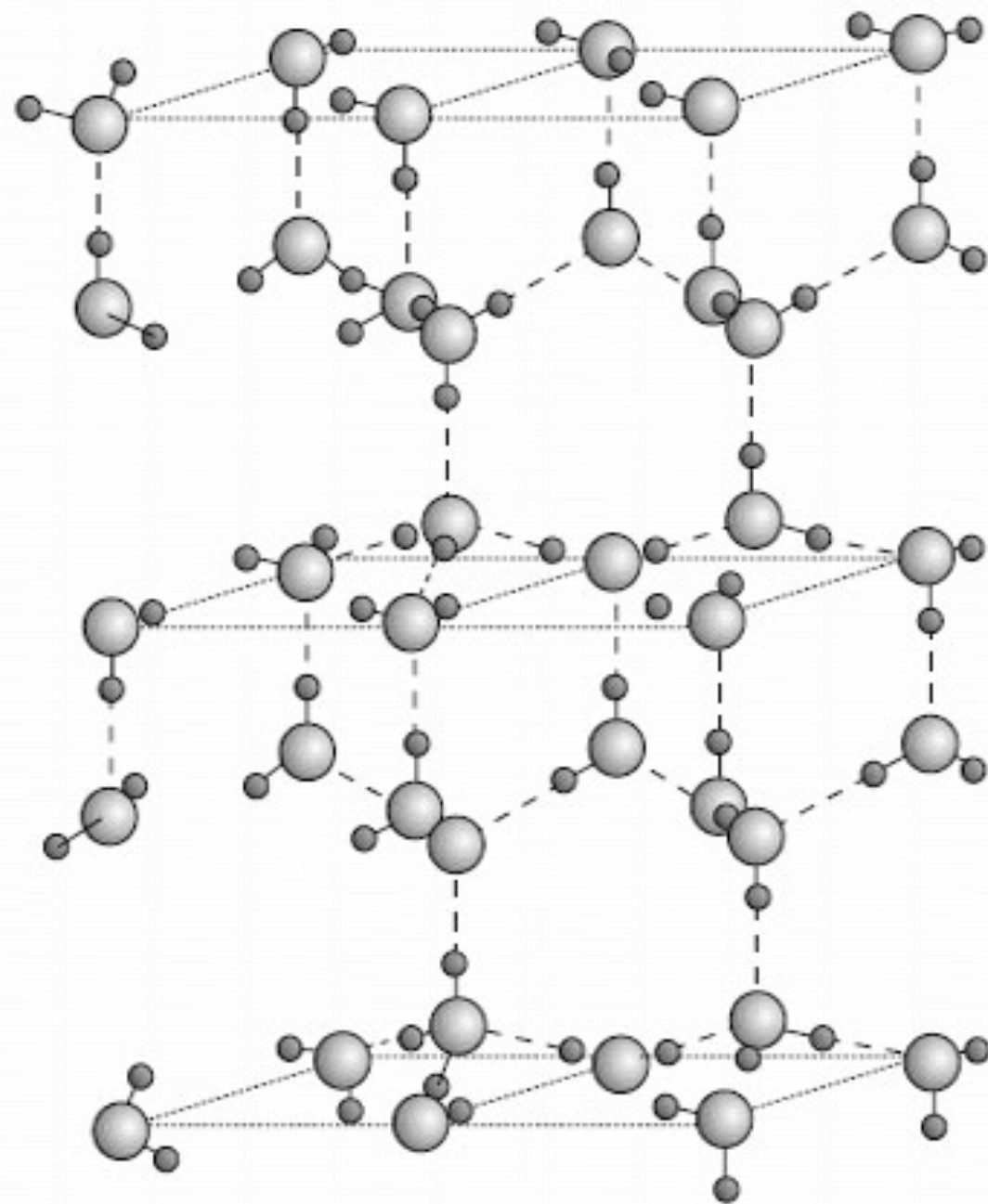


Pyrochlore

freedom of choice for each tetrahedron leads to a  
macroscopic degeneracy: **NO Long Range Order**



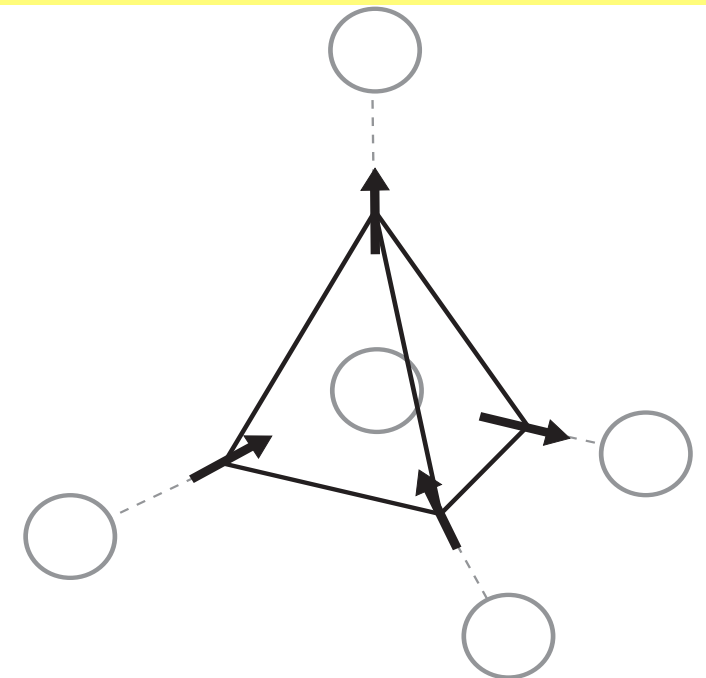
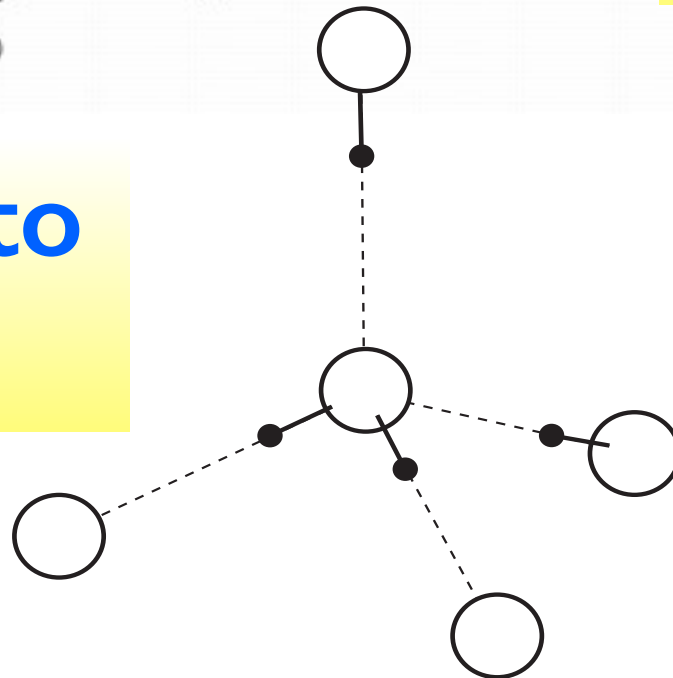
# Structure of Ice



--- Hydrogen bond  
— Covalent bond

**Ferro coupling  
+  $[111]$  anisotropy  
“2 in 2 out”  
6-fold degenerate**

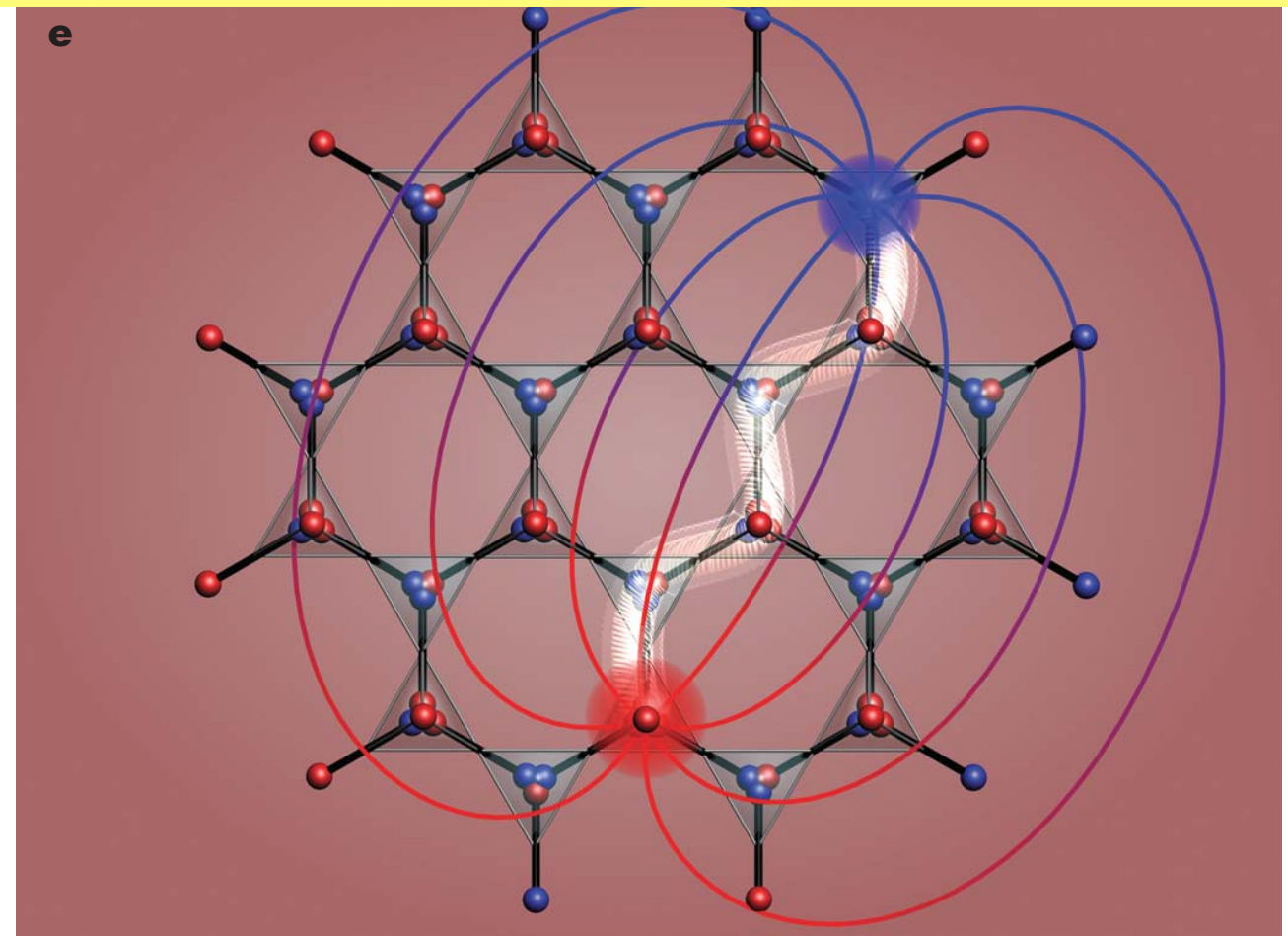
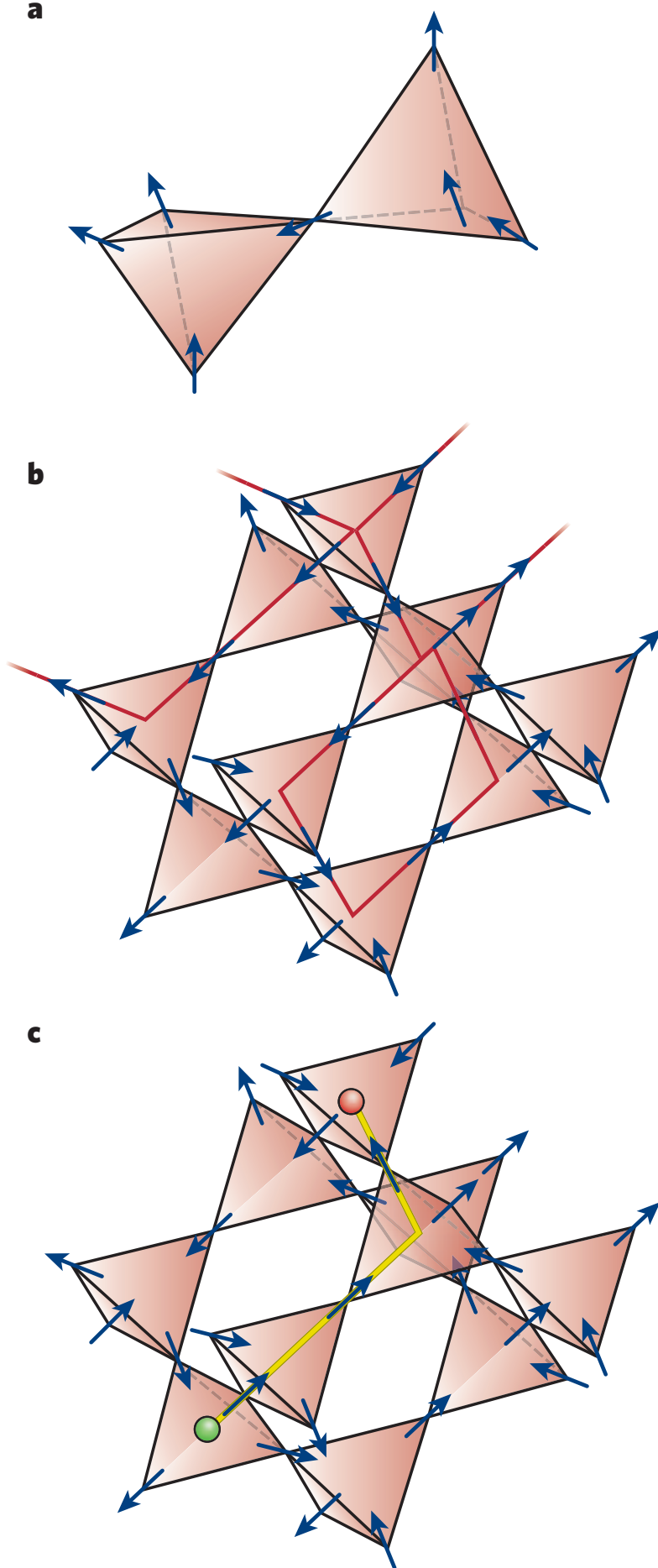
**Correspondance to  
Spin Ice**





# Spin Ice

- Classical macroscopic degeneracy
- Supports monopole excitations
- Rare example of deconfined excitations in 3D



*C. Castelnovo, R. Moessner, and S.L. Sondhi, Nature, 451, 43 (2007)*  
*L. Balents, Nature, 464, 199 (2010)*



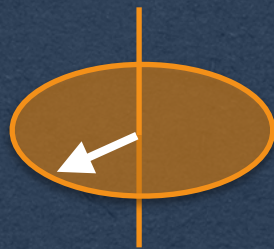
# Real Pyrochlores: playgrounds for frustration



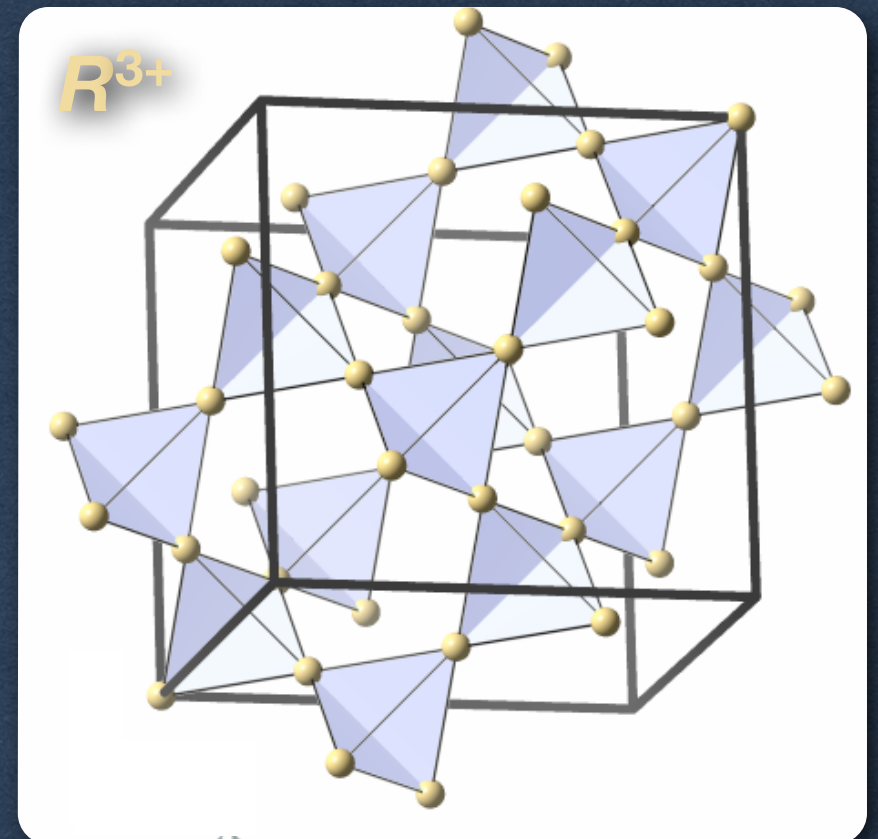
Ising



XY



Heisenberg



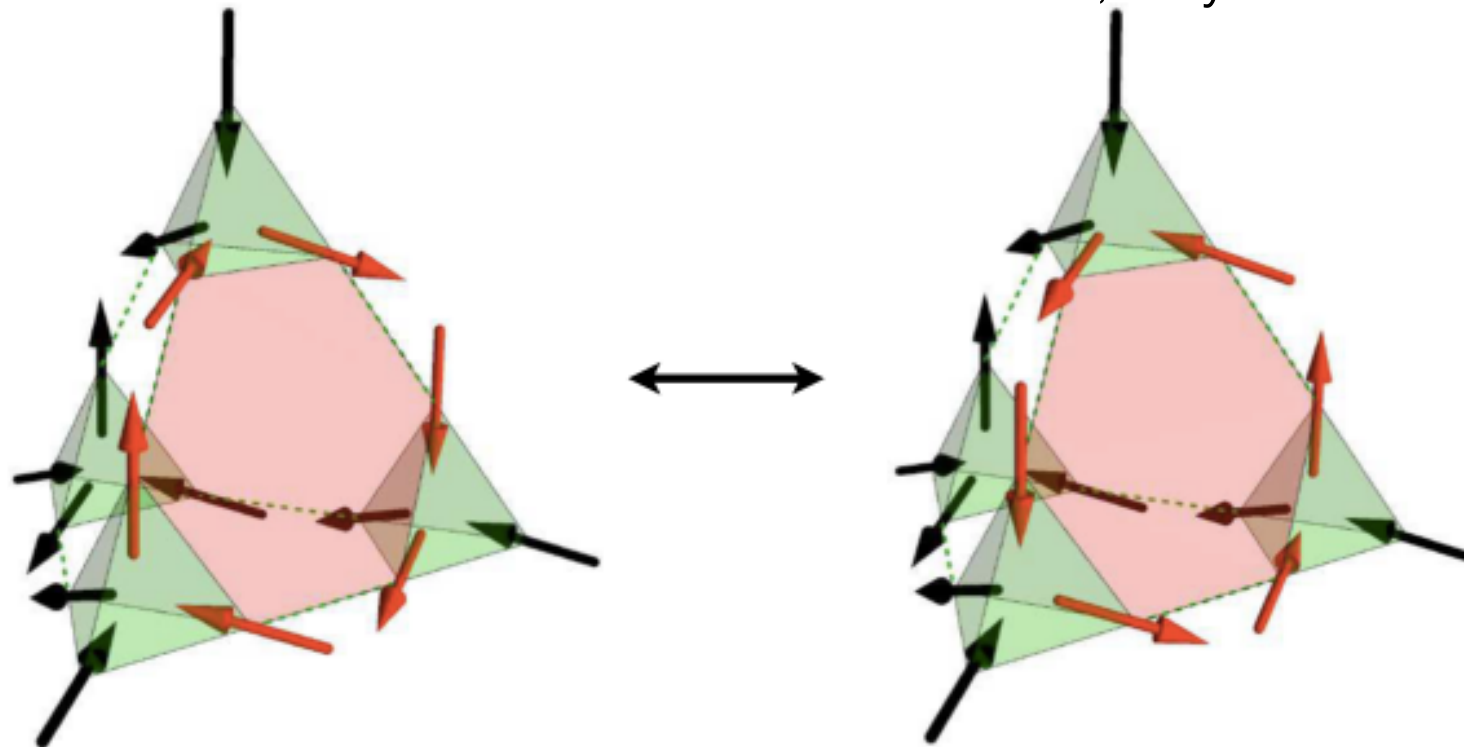
Differences in **Anisotropy** are very important

	Single Ion Anisotropy	Interactions	Ground state
Ho, Dy	Ising	FM	spin ice
Tb	Ising	AFM	spin liquid/QSI
Gd	Heisenberg	AFM	partial order
Er	XY	AFM	“order by disorder”
Yb	XY	FM	“quantum spin ice”



# "Quantum" Spin Ice

O. Benton et al, Phys. Rev. B **86**, 2012



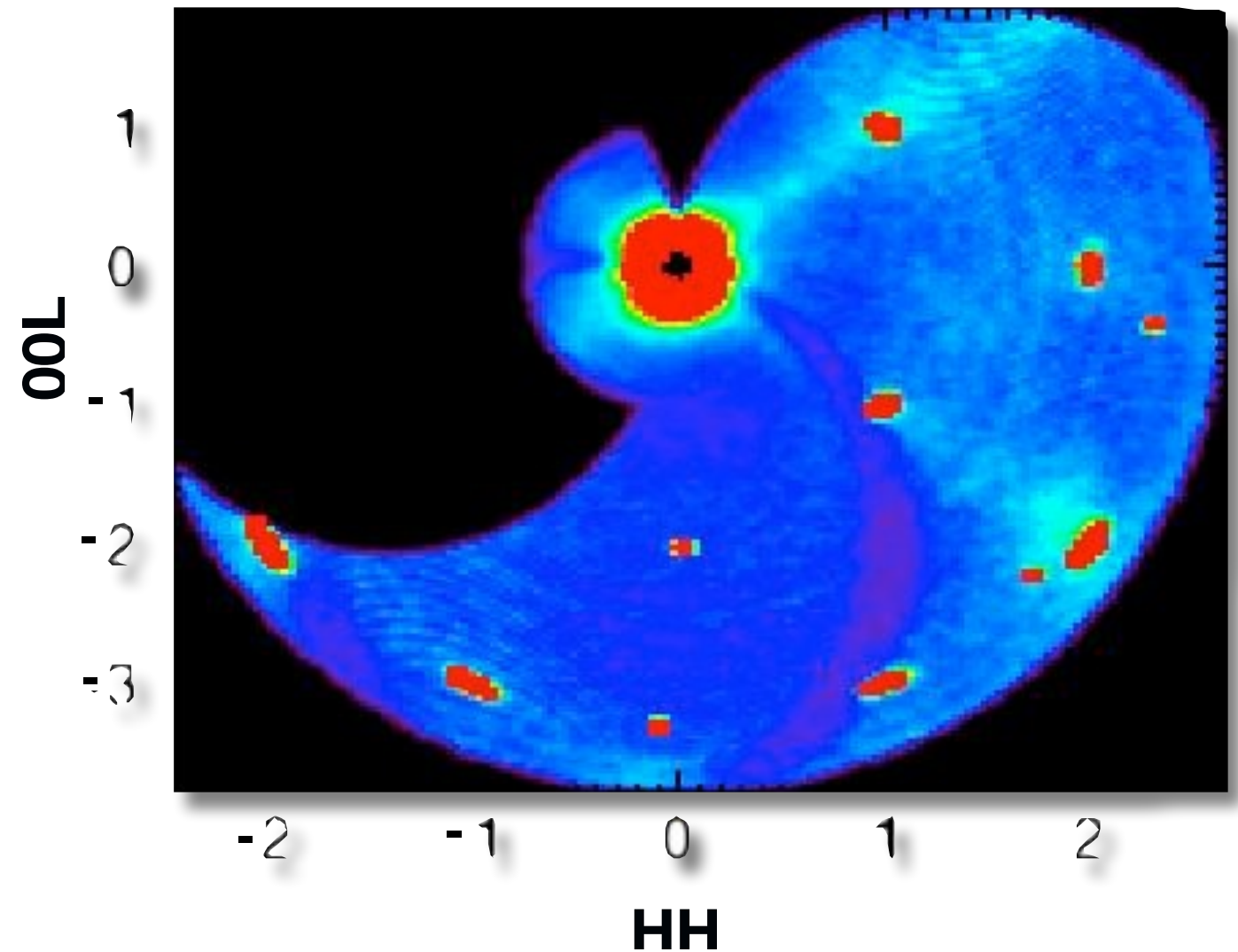
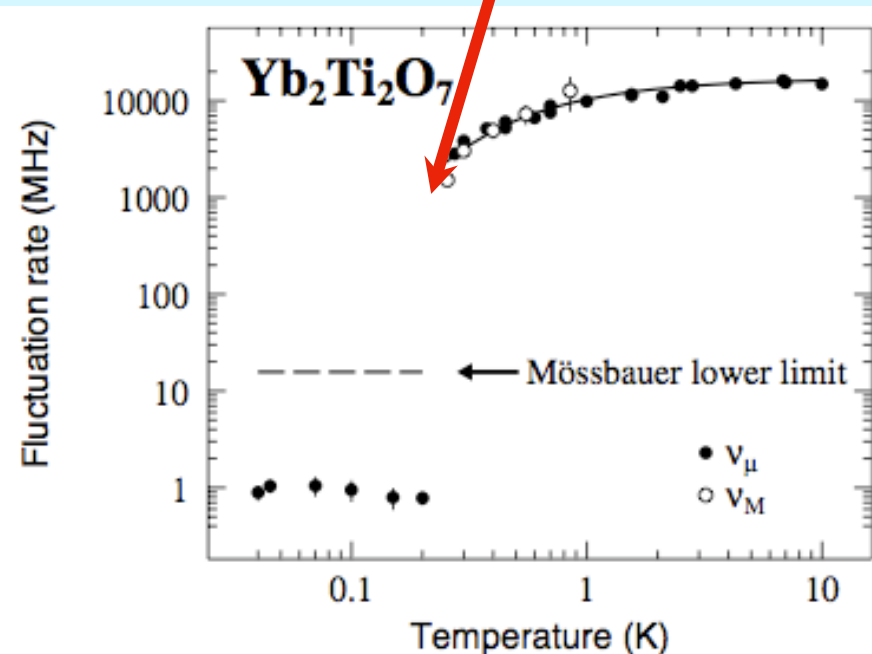
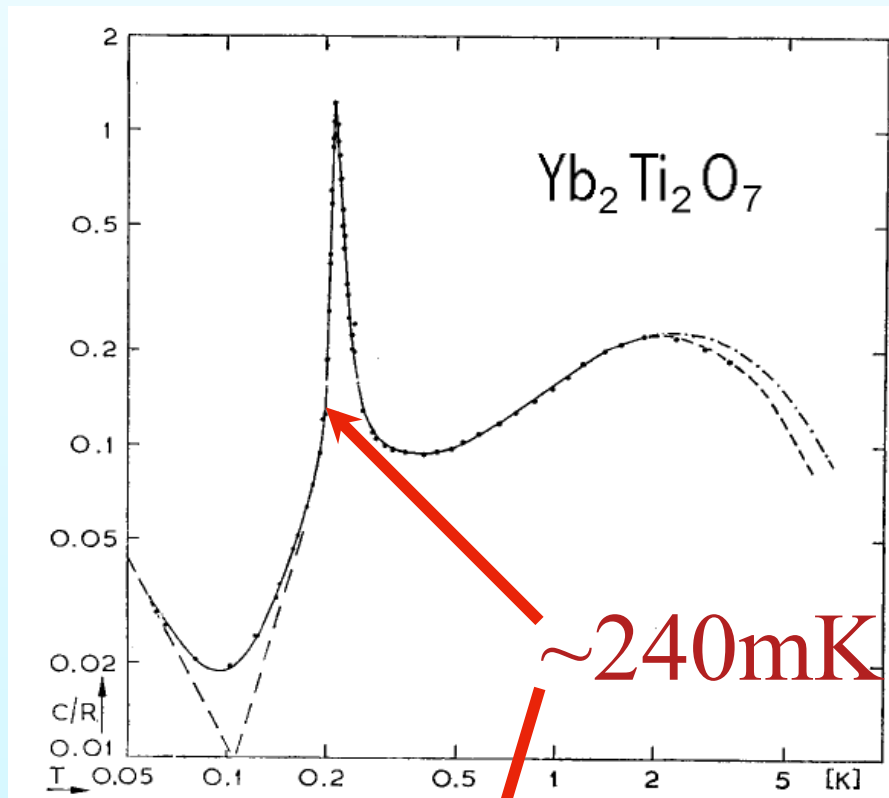
$$\vec{\nabla} \cdot \vec{B} = \rho_m$$
$$\vec{B} = \vec{\nabla} \times \vec{A}$$
$$\vec{E} = -\frac{\partial \vec{A}}{\partial t}$$

$$\mathcal{H}_{\text{U}(1)} = \frac{\mathcal{U}}{2} \sum_{\langle \mathbf{r}\mathbf{r}' \rangle} [(\nabla_{\mathbf{O}} \times \mathcal{A})_{\mathbf{r}\mathbf{r}'}]^2 + \frac{\mathcal{K}}{2} \sum_{\langle \mathbf{s}\mathbf{s}' \rangle} \mathcal{E}_{\mathbf{s}\mathbf{s}'}^2$$

- Can tunnel between ice rules states
- Introduces *fluctuations* in the gauge field
  - **Electric monopoles** — coherent, propagating wavepacket of ice configurations
  - **Magnetic monopoles** — violate ice rules, i.e. 3-in 1-out
  - **Gauge photons** — transverse fluctuations of gauge field



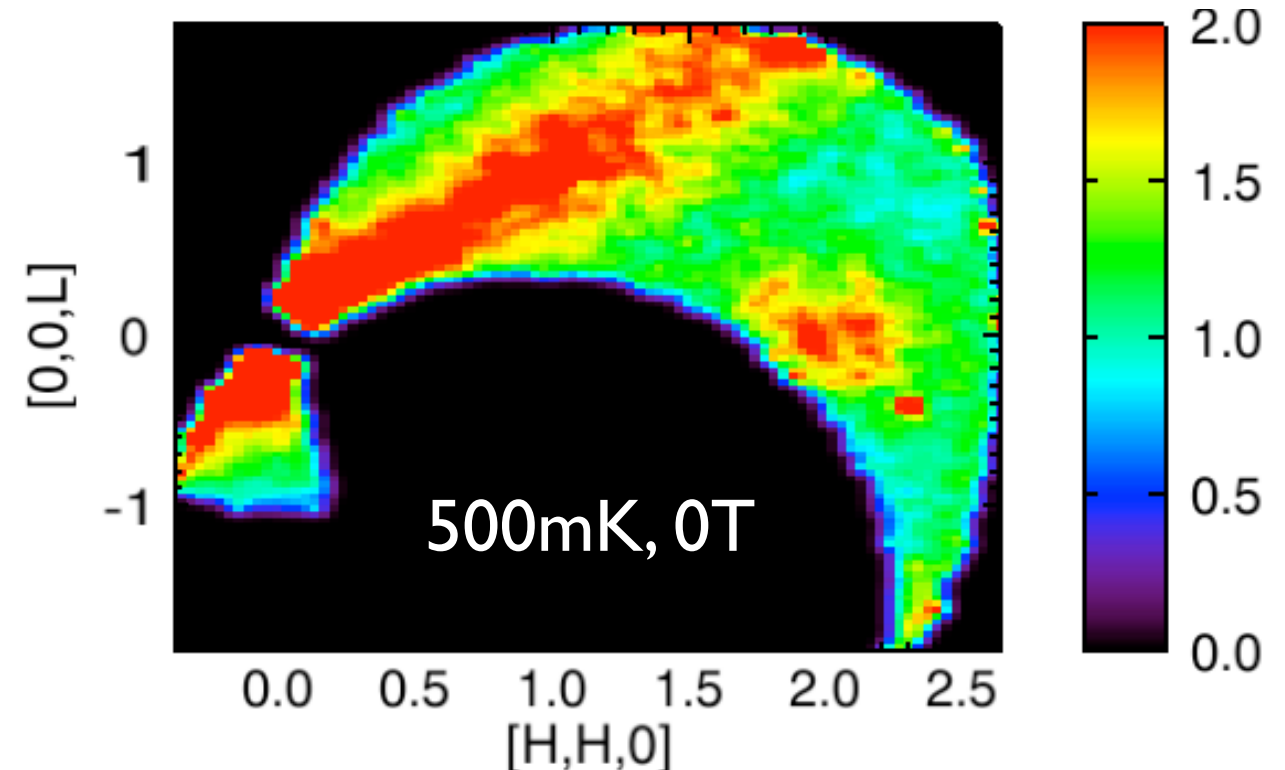
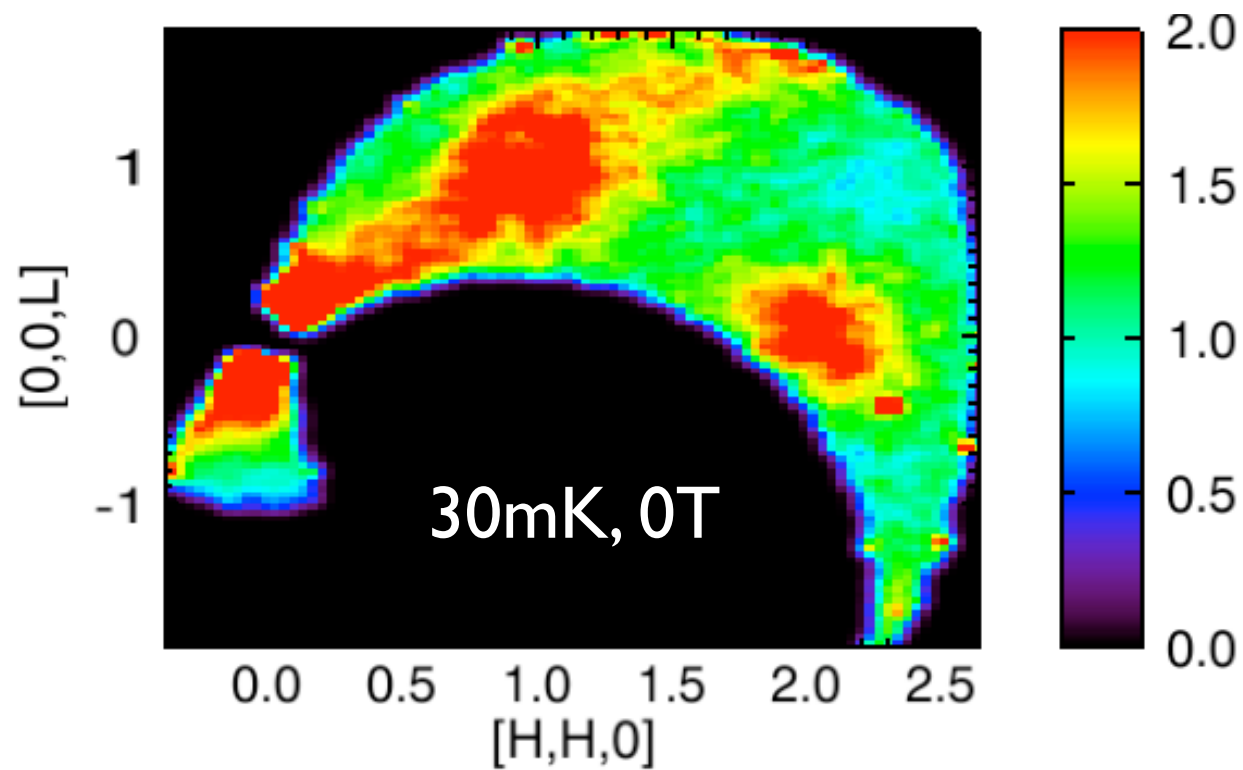
# $\text{Yb}_2\text{Ti}_2\text{O}_7$ by the numbers:



- Ferromagnetic “XY” pyrochlore
- “ $T_C$ ”  $\sim 240$  mK
- $CW_T \sim +0.6$  K       $g_\perp/g_\parallel \sim 2.4$

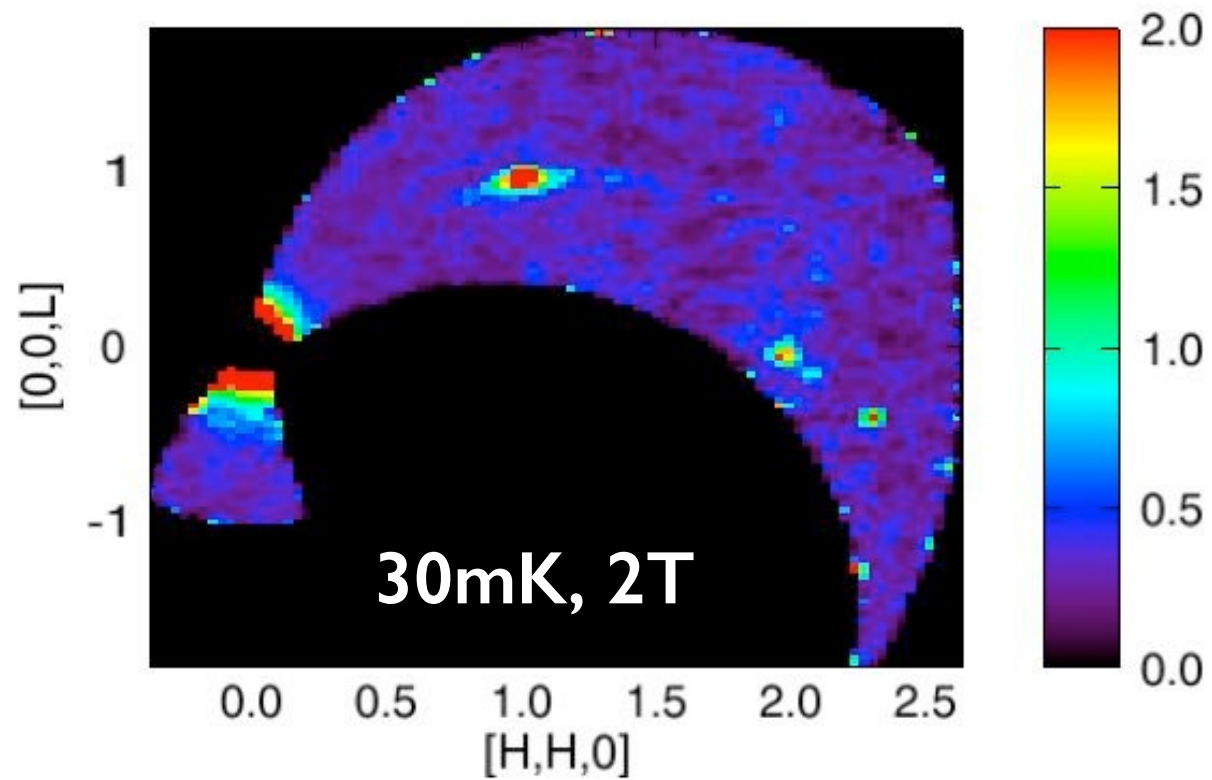
# Development of 3D Correlations

$E = [0.1, 0.3]$  meV (Quasi elastic)

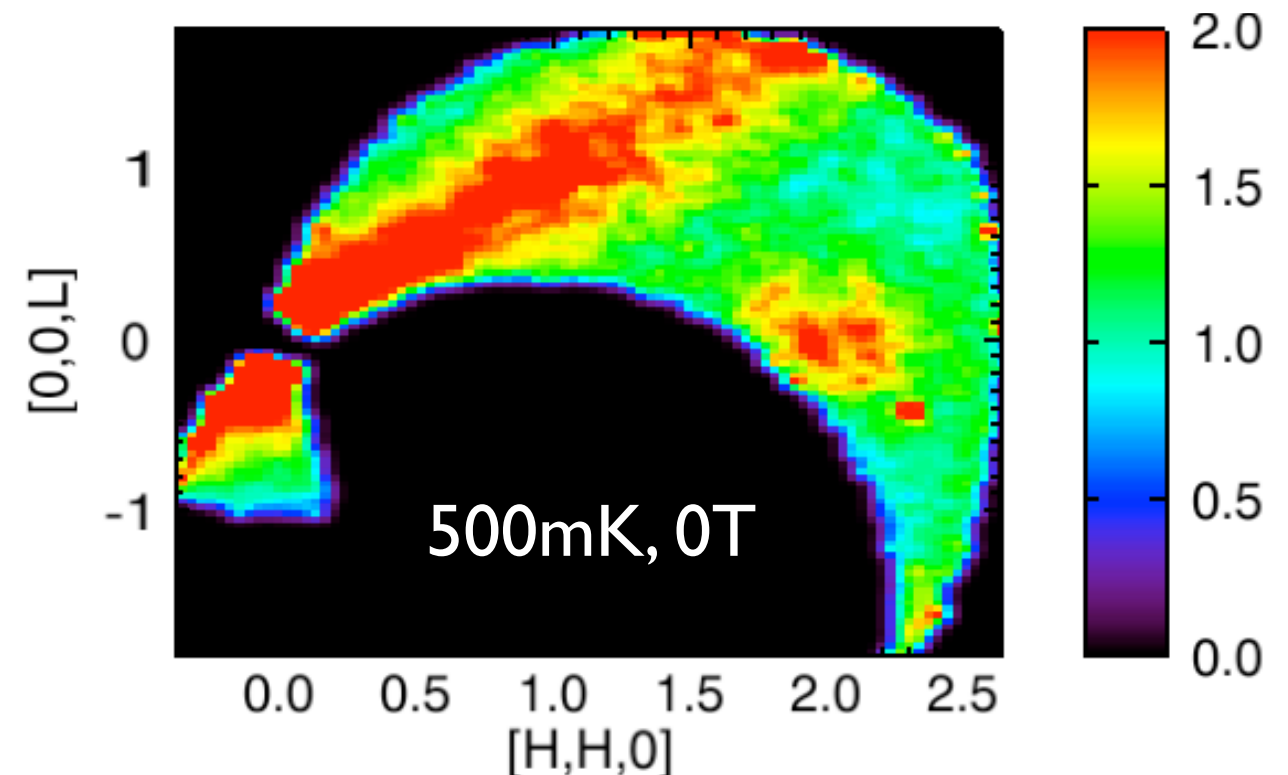
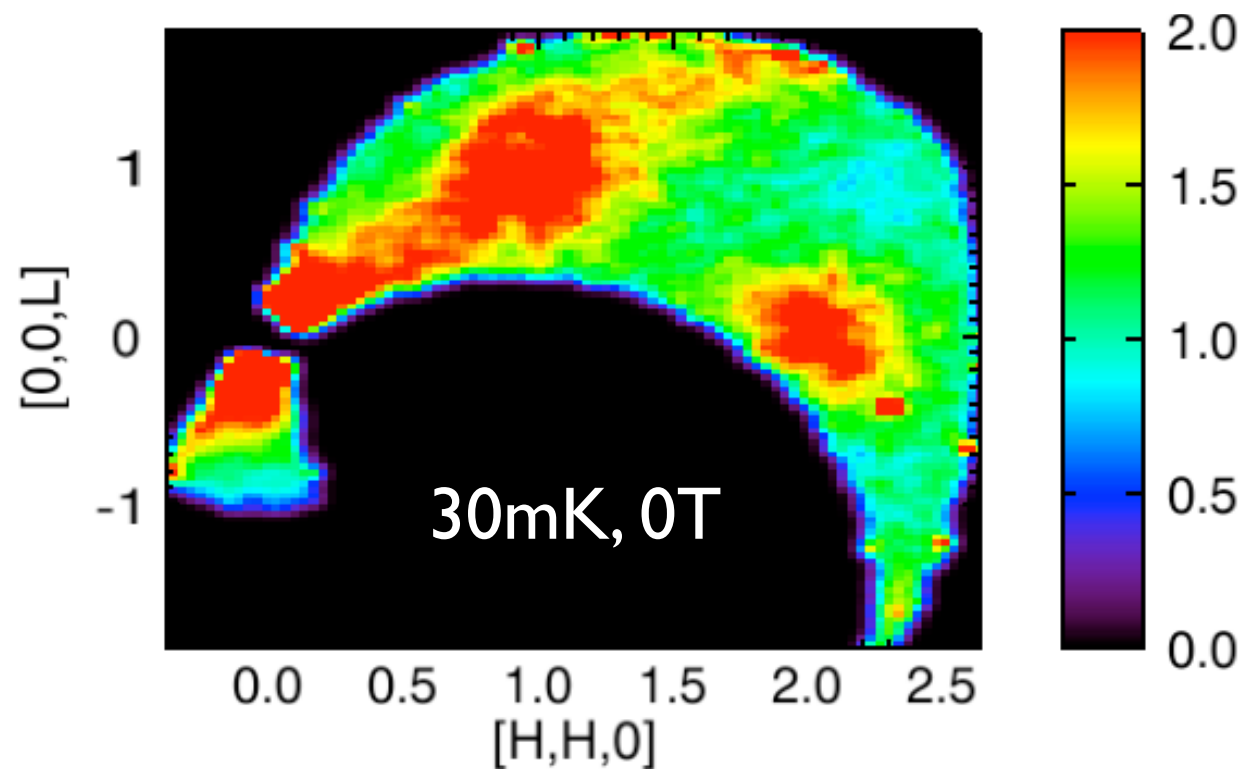




# Application of a Field

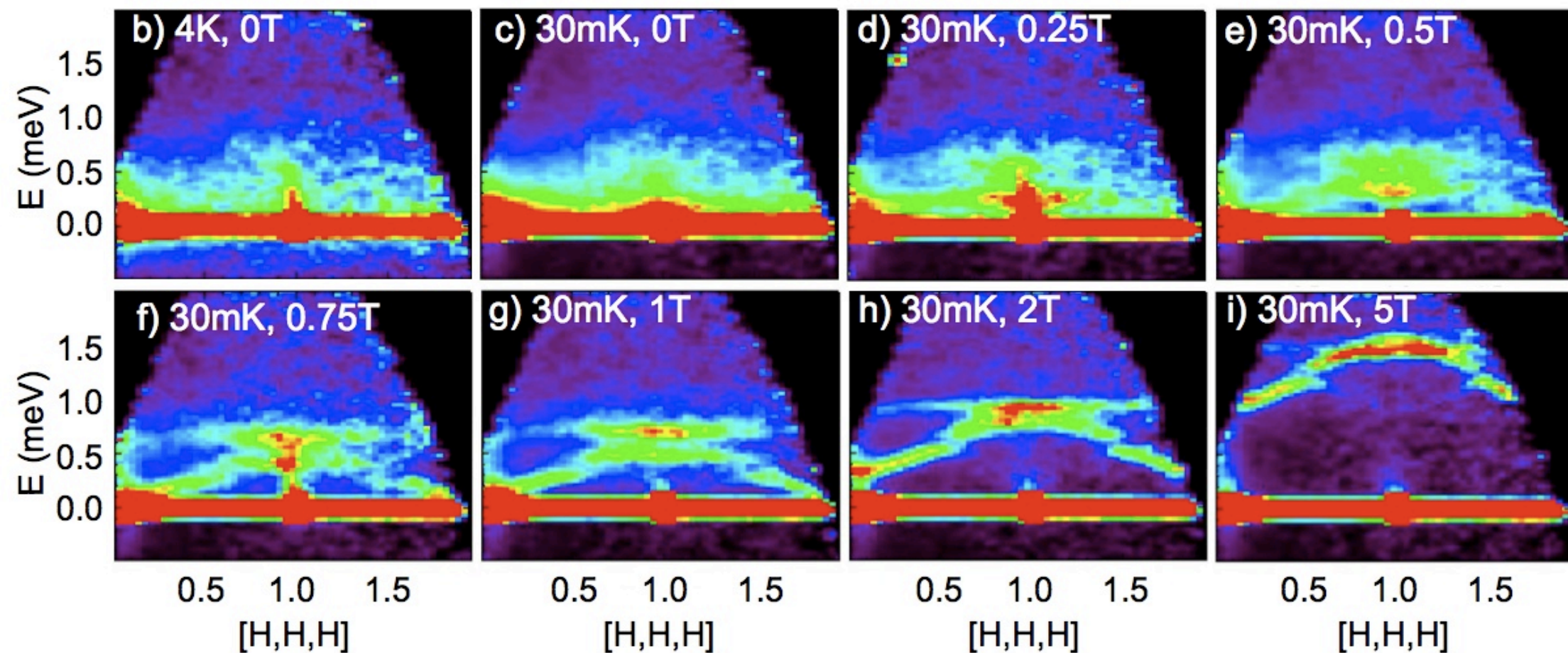
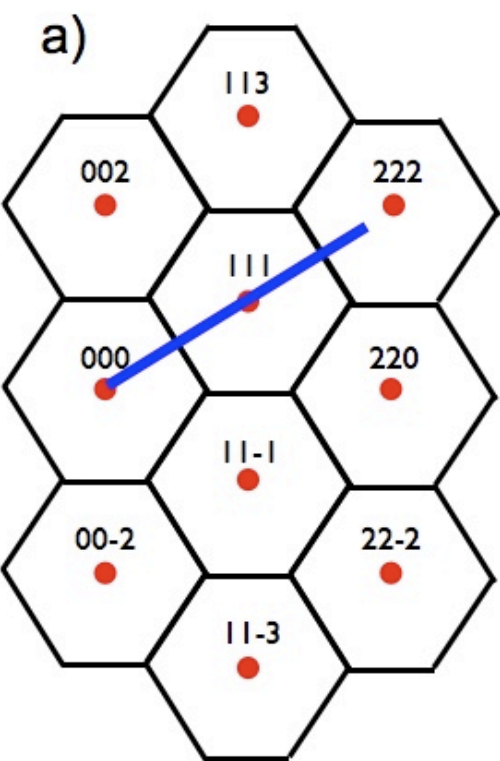


**Field removes diffuse scattering**

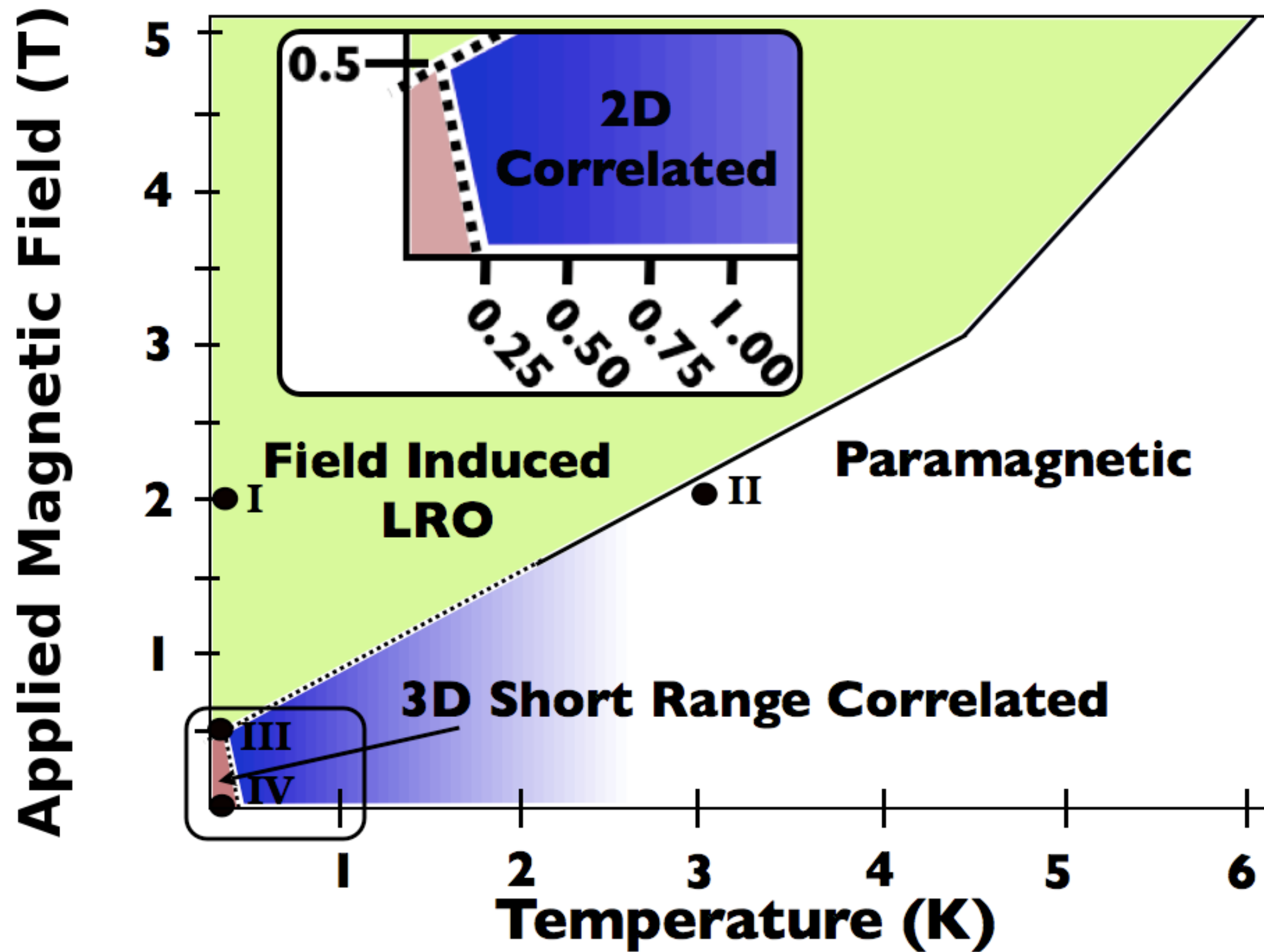


Weak magnetic field //  $[110]$  induces LRO:

*appearance of long-lived spin waves at low  $T$  and moderate  $H$*



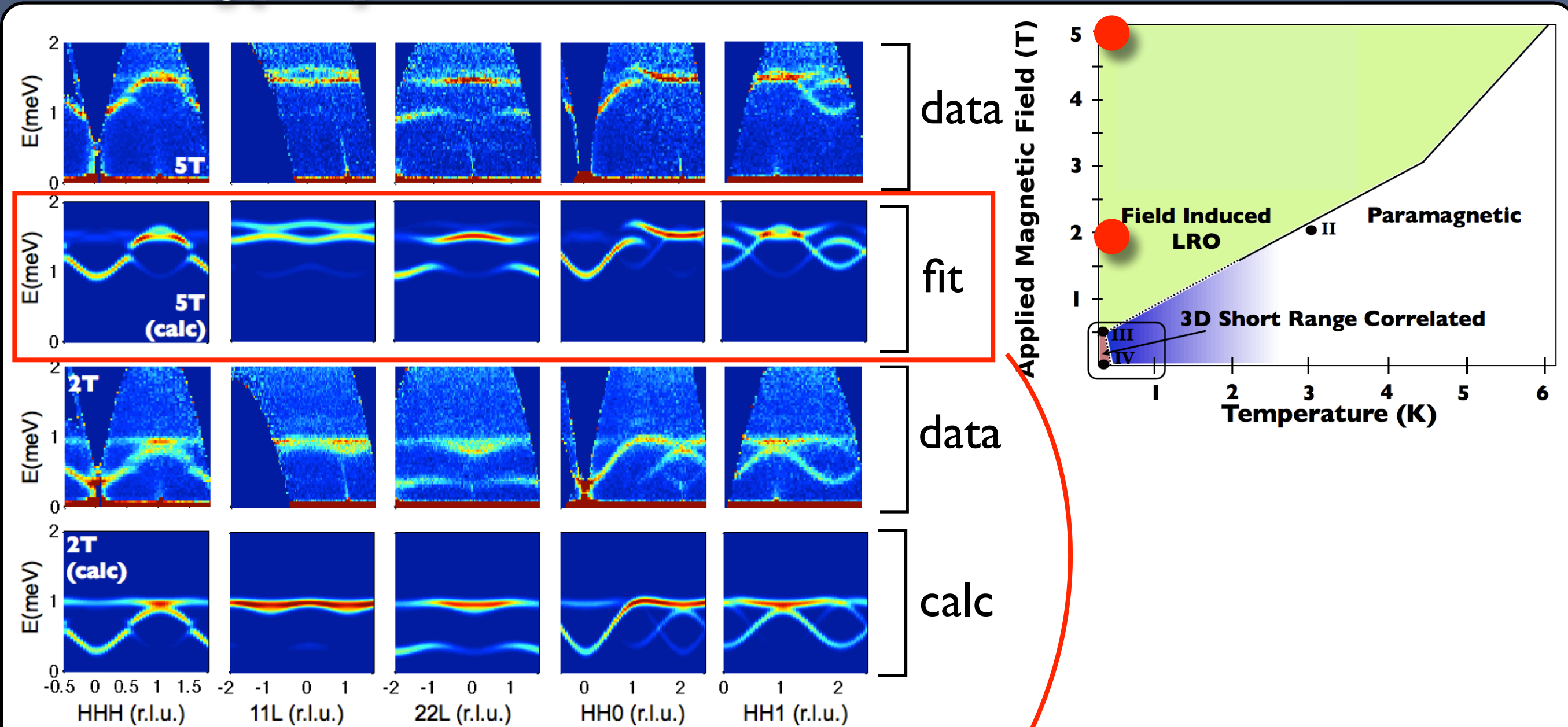




*K. A. Ross, J. P. C. Ruff, C. P. Adams, J. S. Gardner, H. A. Dabkowska, Y. Qiu, J. R. D. Copley, and B. D. Gaulin, Phys. Rev. Lett. 103, 227202 (2009)*

# Yb<sub>2</sub>Ti<sub>2</sub>O<sub>7</sub> field polarized state

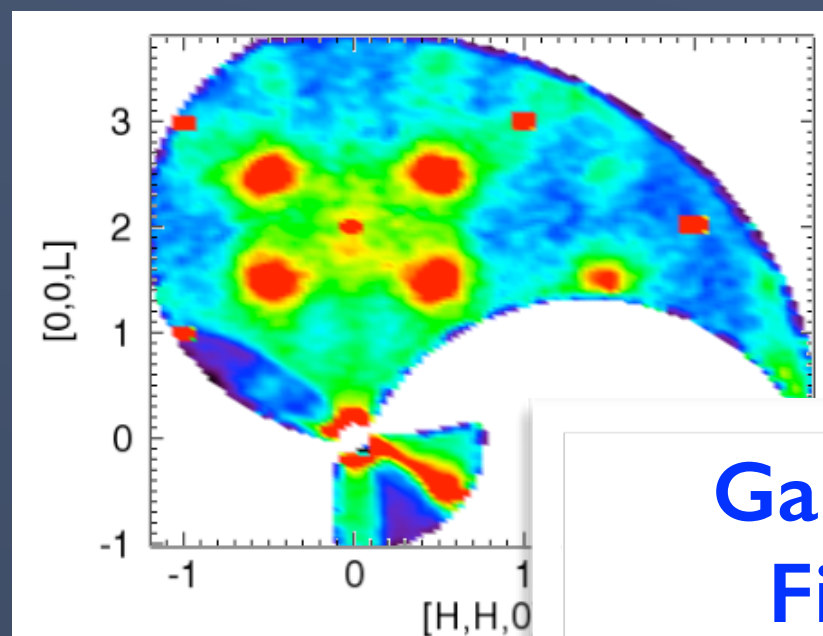
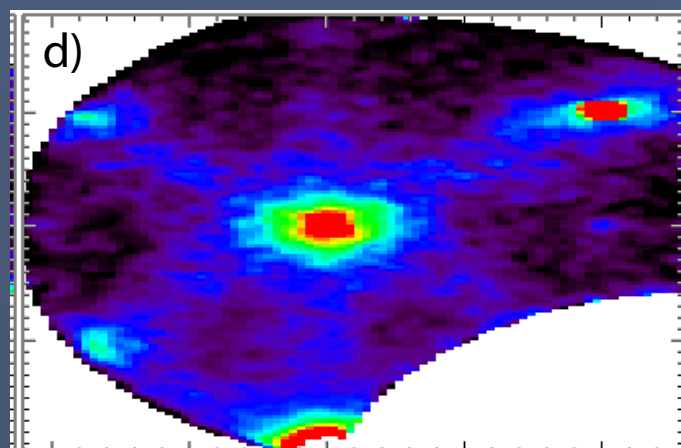
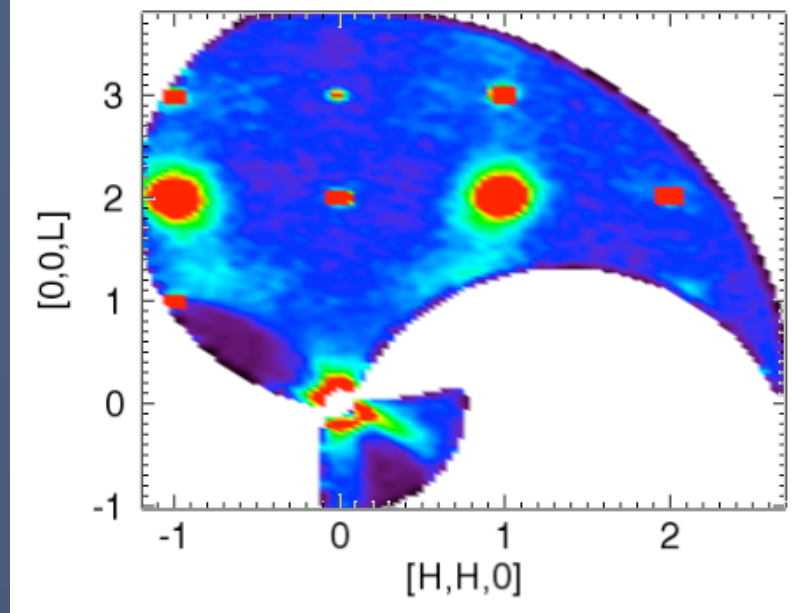
H along [1-10]



“Quantum Spin Ice”

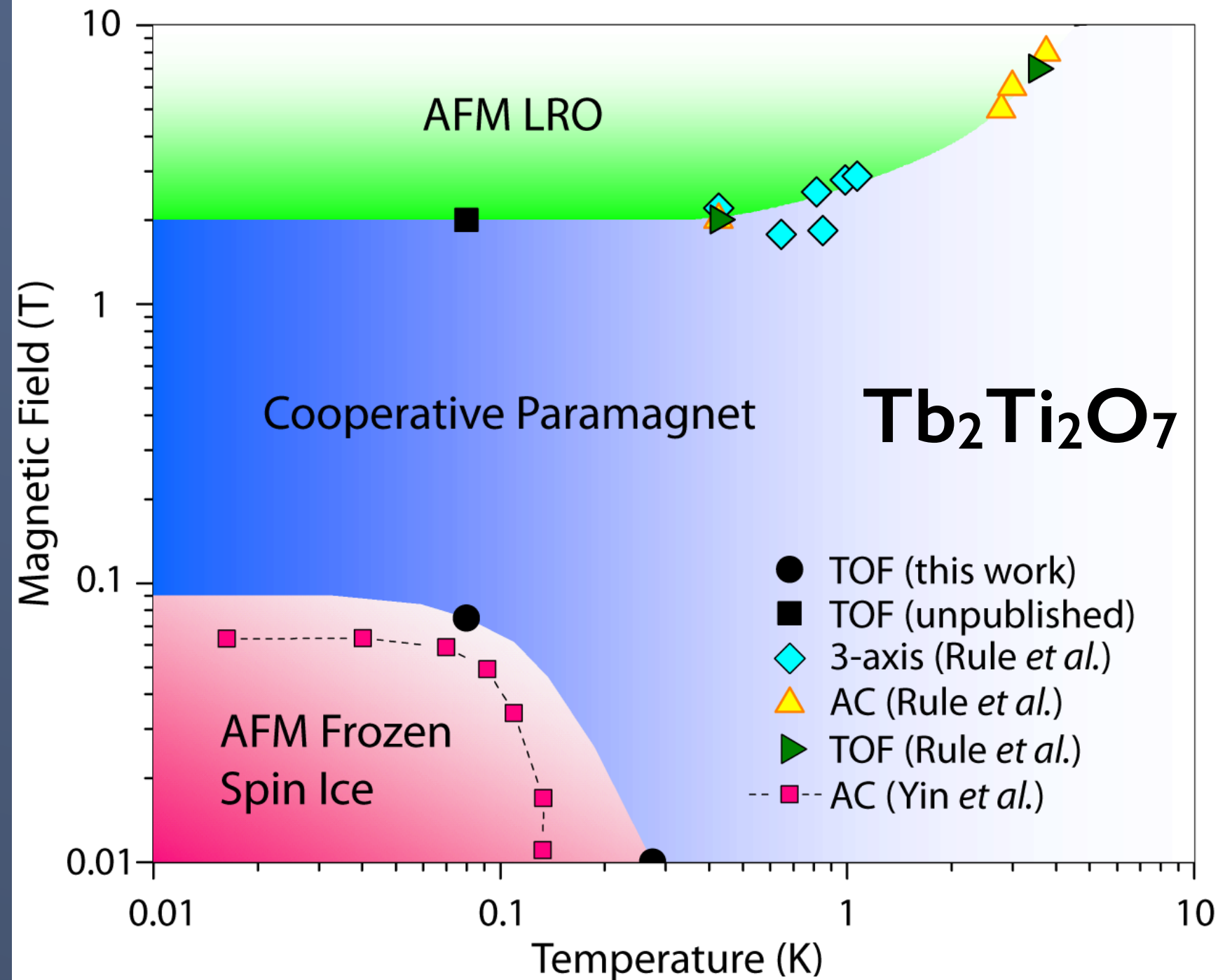
$$J_{zz} = 0.17 \pm 0.04, J_{\pm} = 0.05 \pm 0.01, J_{\pm\pm} = 0.05 \pm 0.01, J_{z\pm} = -0.14 \pm 0.01 \quad (\text{meV})$$



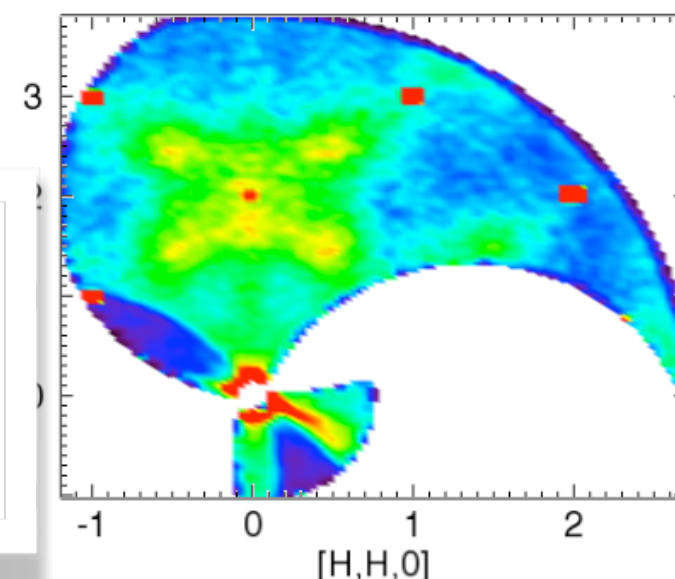


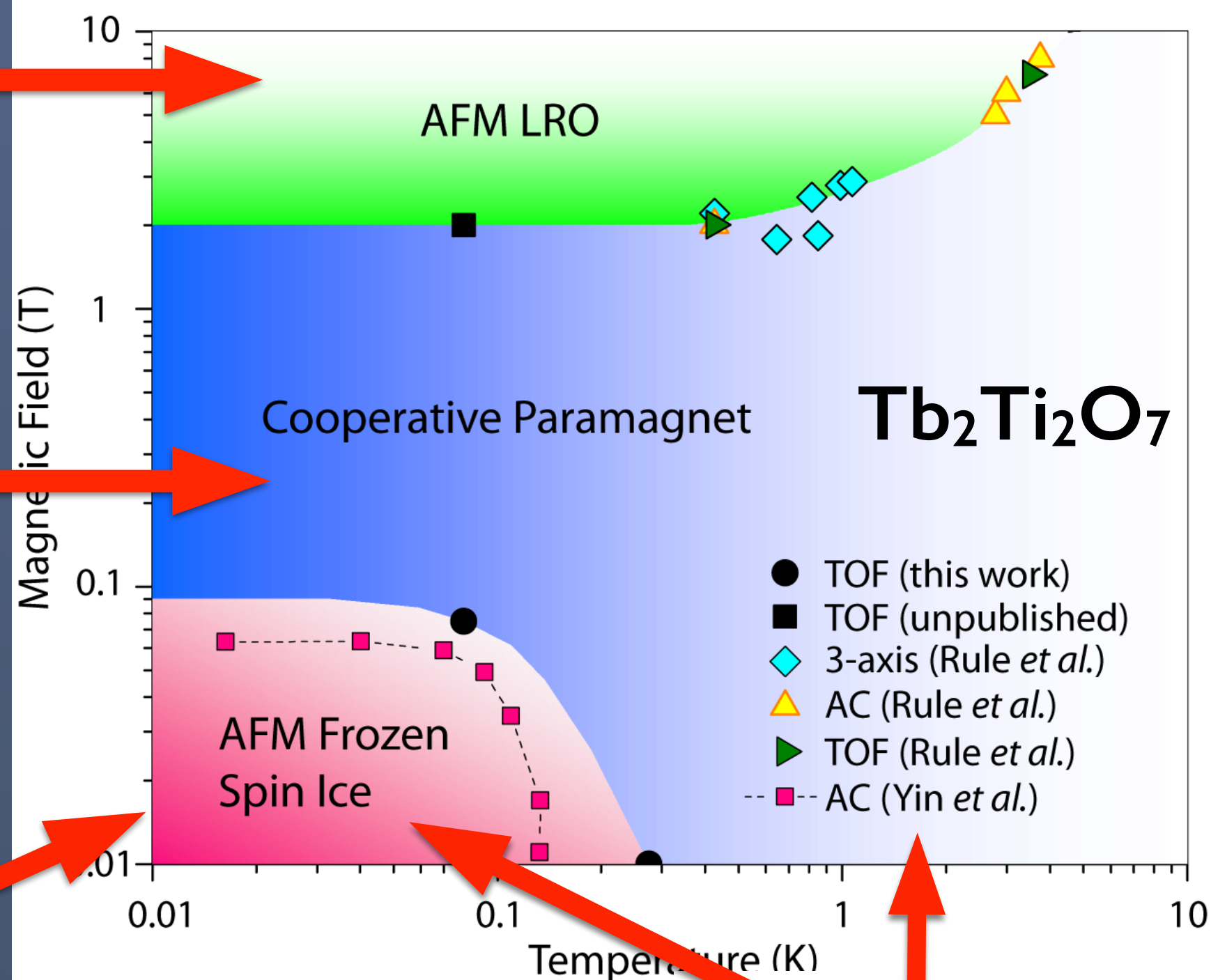
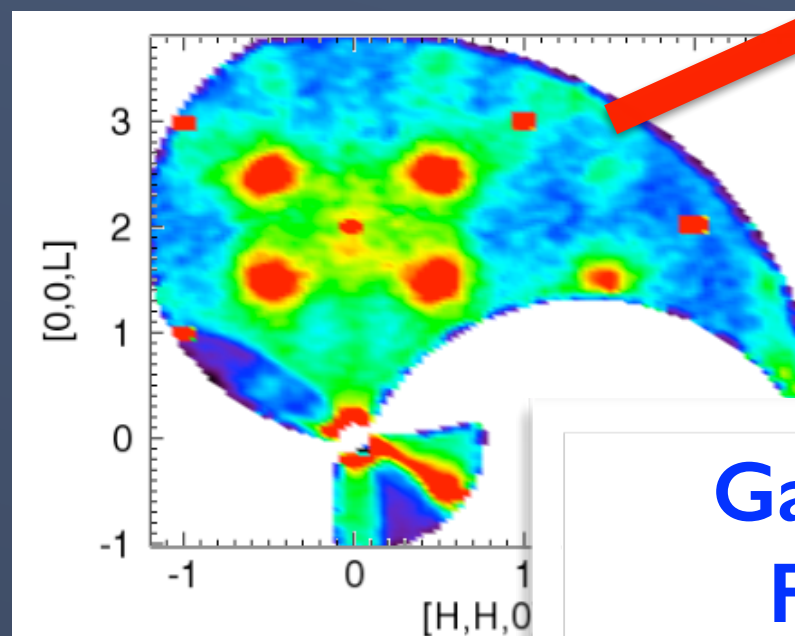
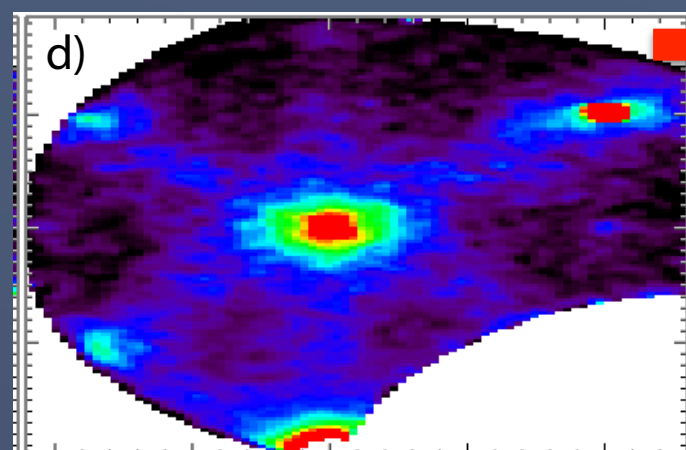
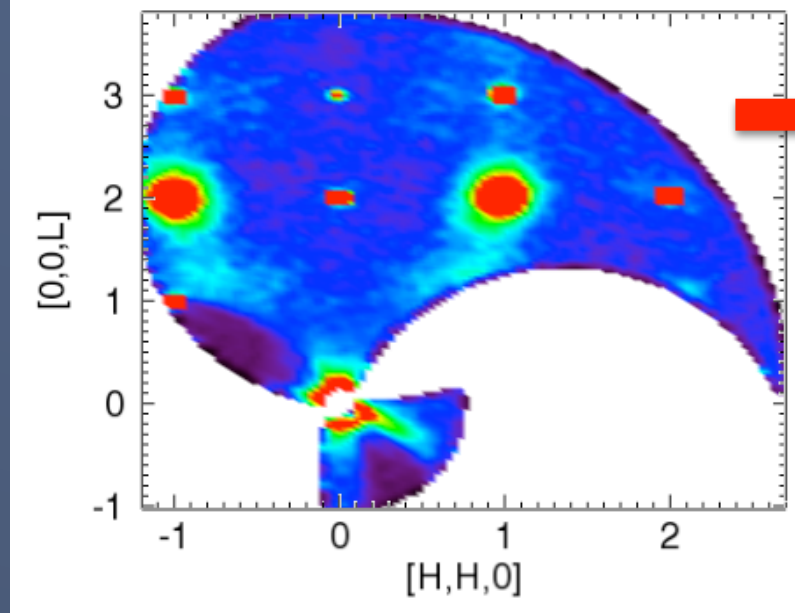
**Gapped  
Field  
Cooled State**

**Gapless  
Zero-Field  
Cooled State**



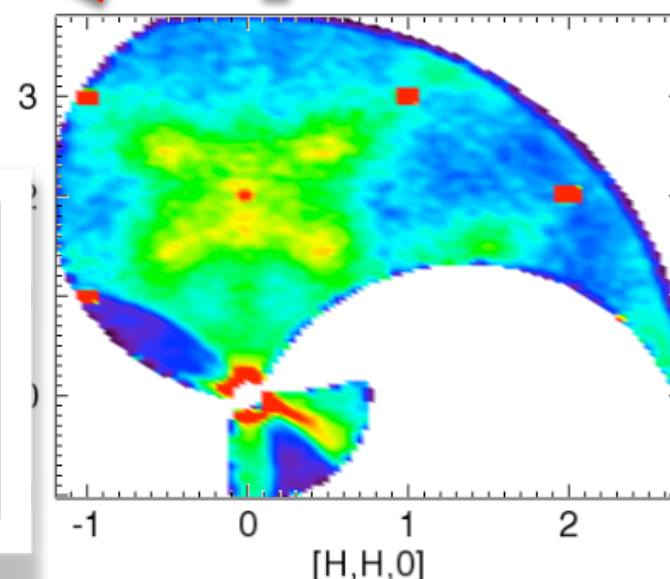
Tb<sub>2</sub>+xTi<sub>2</sub>-xO<sub>7</sub> 5A T=80mK xneg H=0T, E=[-0.1,0.1] meV ZFC





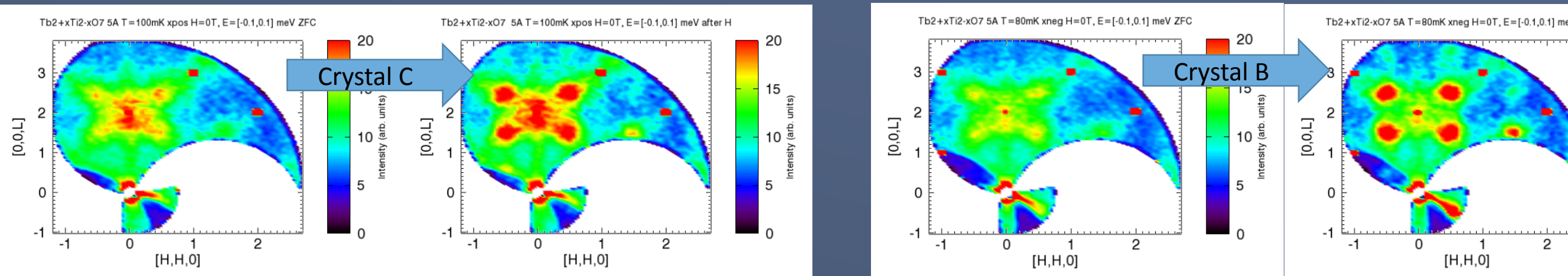
**Gapped  
Field  
Cooled State**

**Gapless  
Zero-Field  
Cooled State**



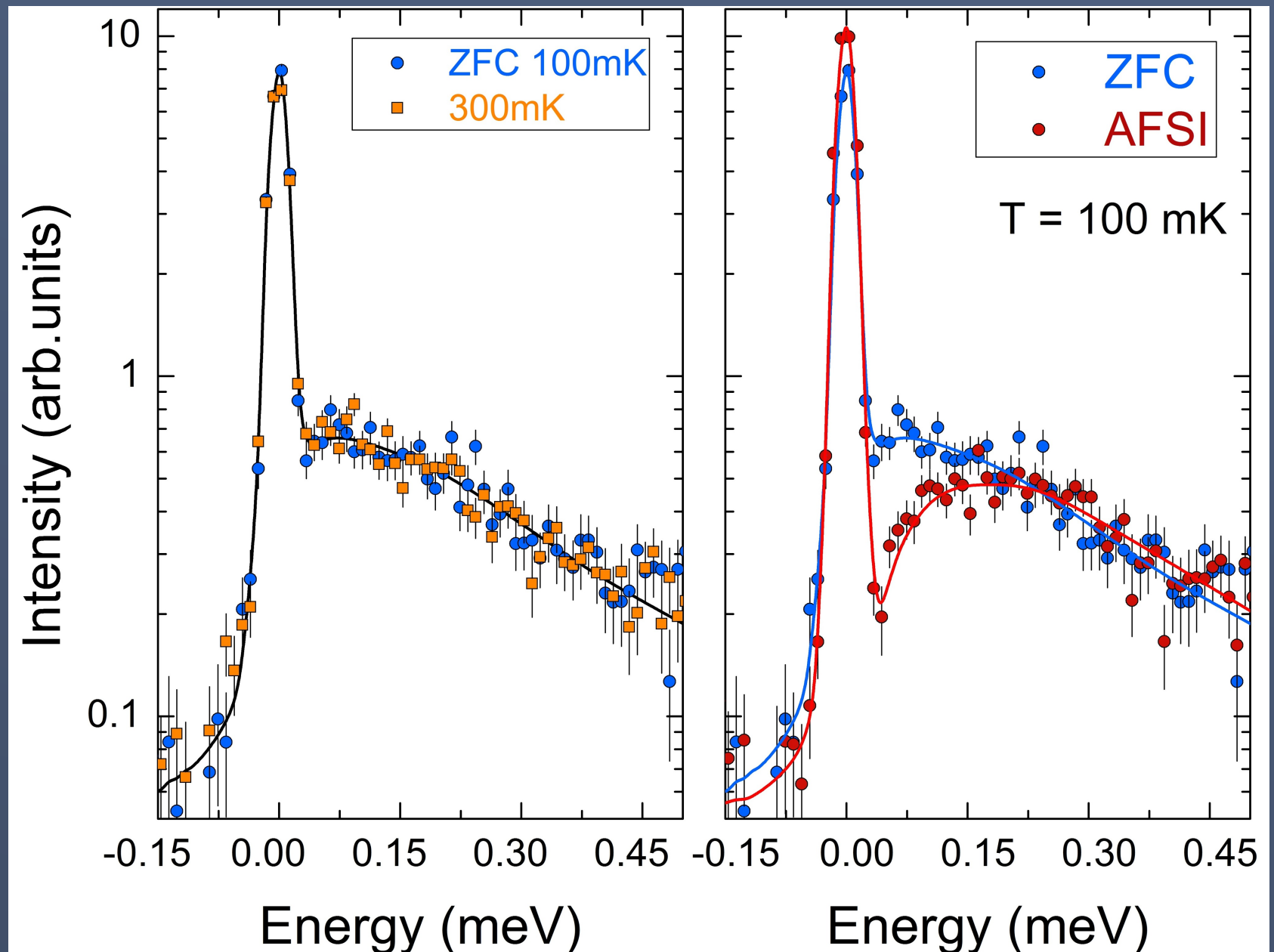


# Gapped “ordered AF” spin ice state in $\text{Tb}_2\text{Ti}_2\text{O}_7$



Magnetic spectral  
suppression  
in FC state is robust

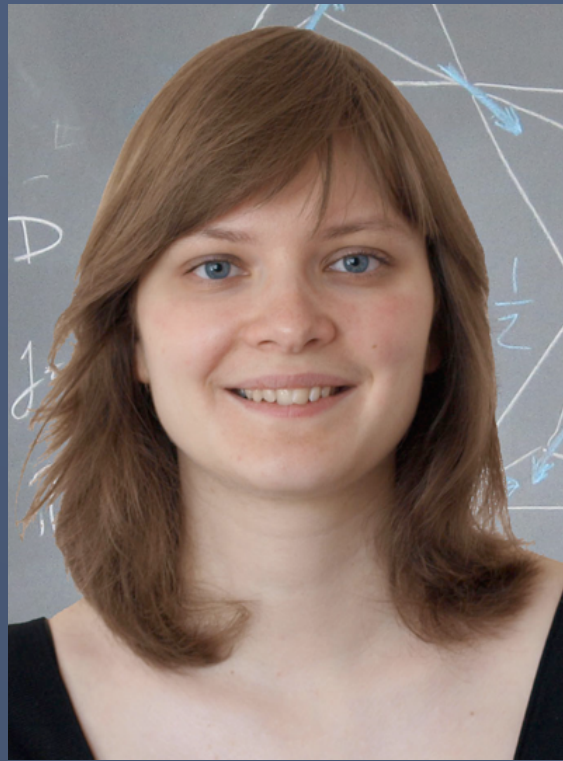
Dynamic spectral  
weight transferred  
to elastic scattering





# Thank You for 15 Years of Collaboration

Lucile Savary Jonathan Gaudet



Sara

Haravifard

Kate Ross

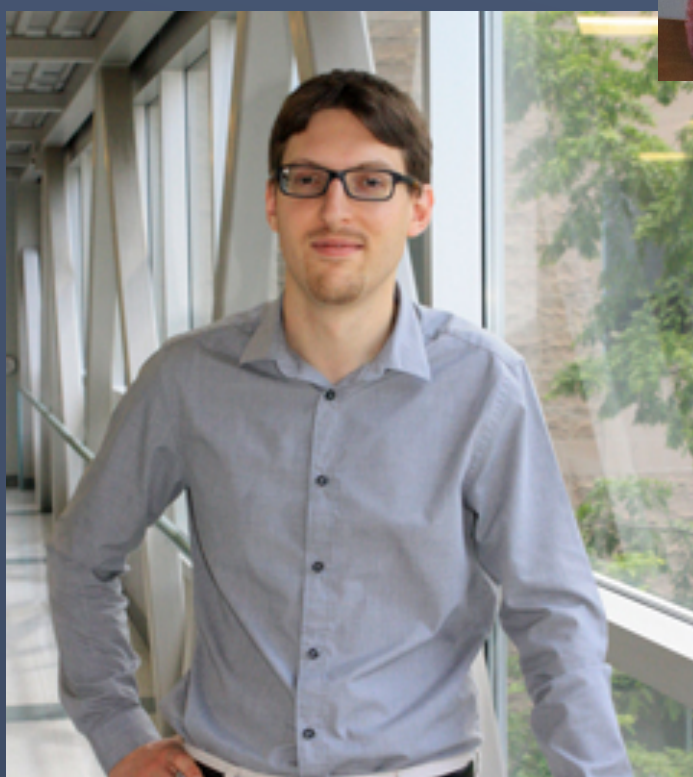


Pat Clancy



Edwin Kermarrec

Alannah Hallas



Katharina Fritsch



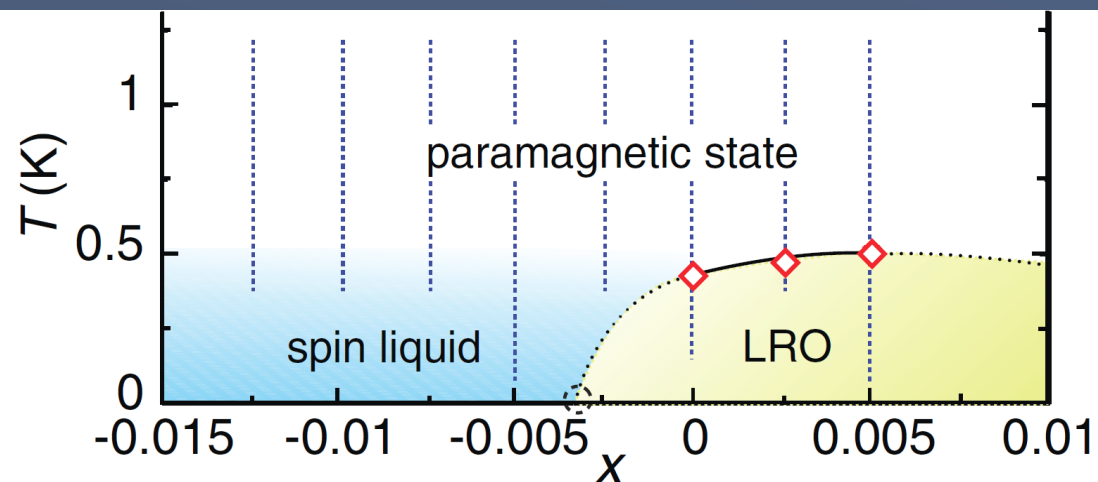
Jacob Ruff



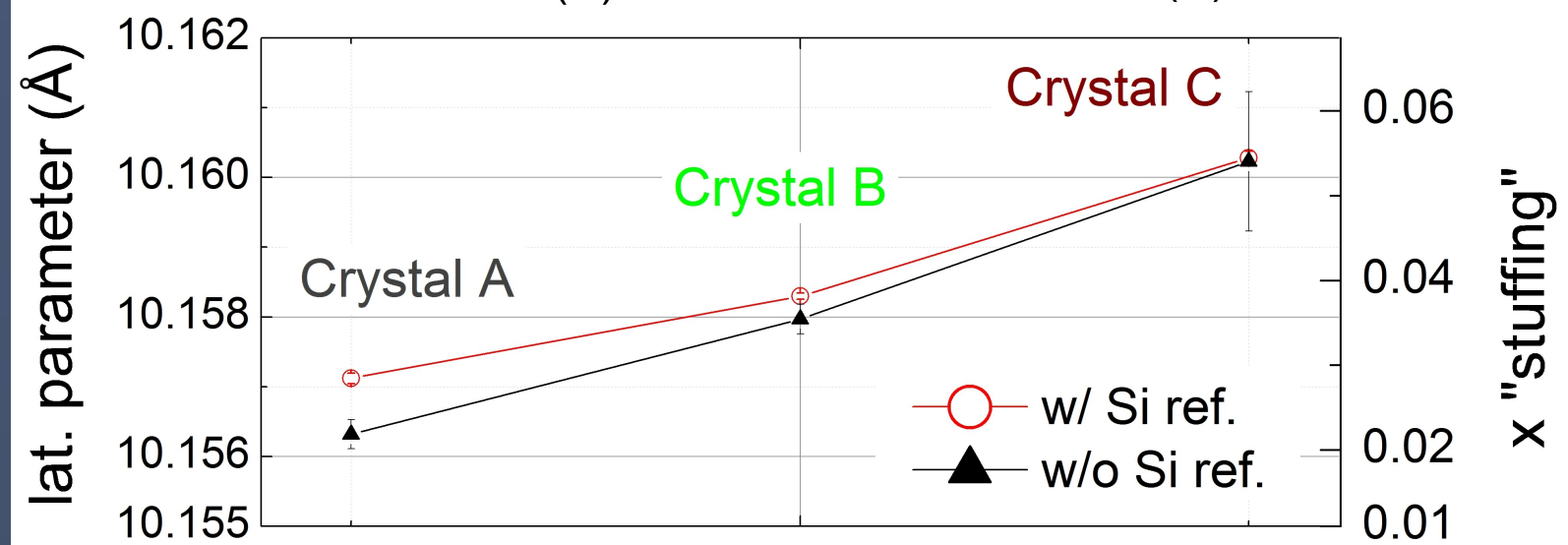
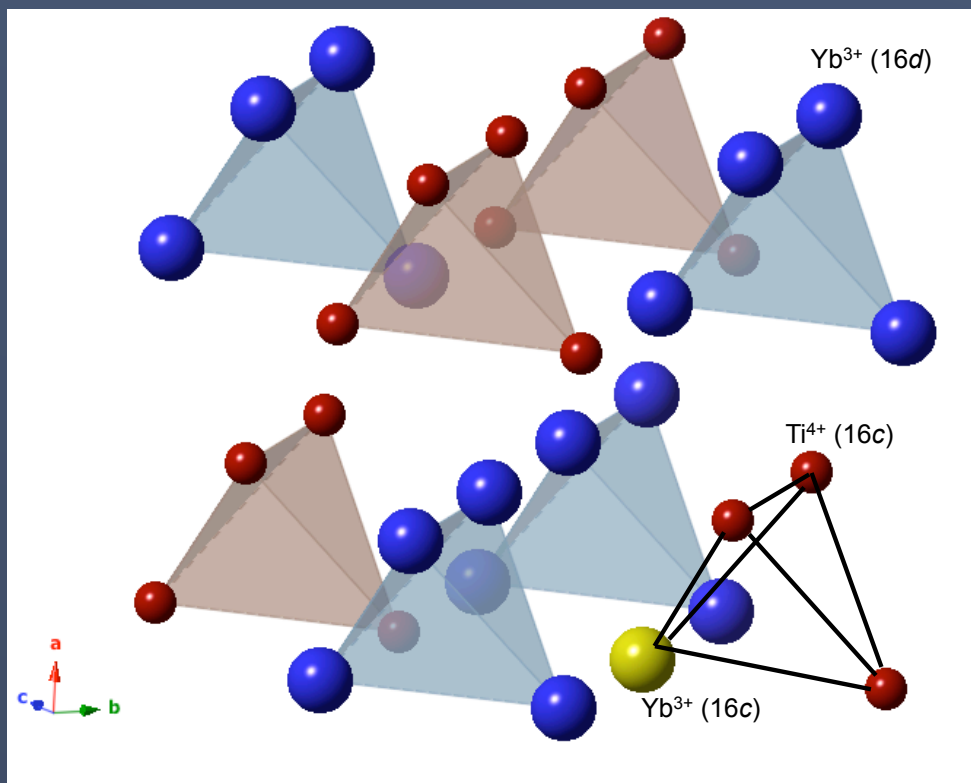
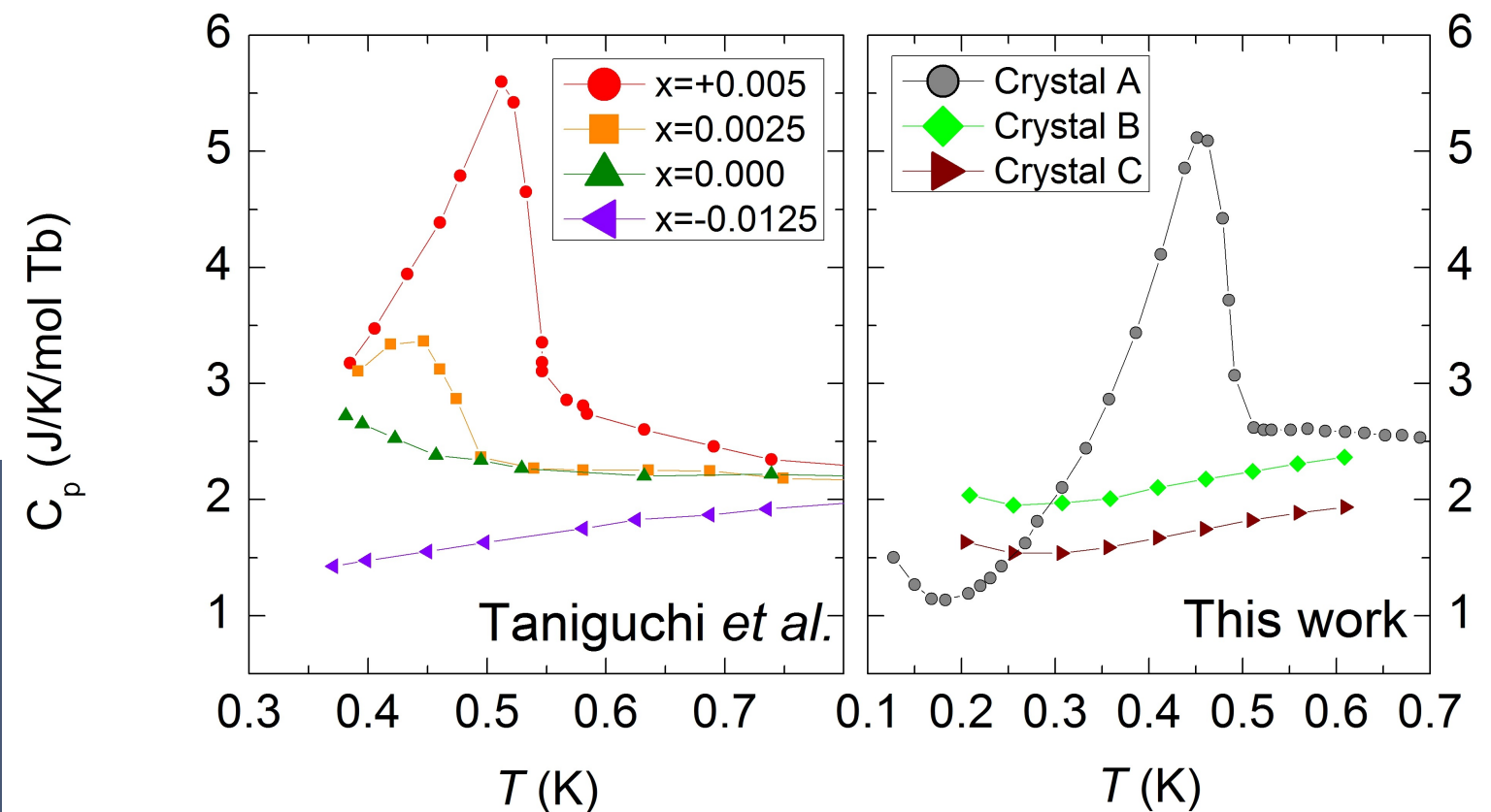
Miles  
Couchman



# New Single Crystals Grown with varying Tb:Ti i.e. “stuffing” - New samples have **no** Cp anomaly



Taniguchi et al, Phys. Rev. B, 87, 060408(R), 2013.



# Anisotropic Exchange

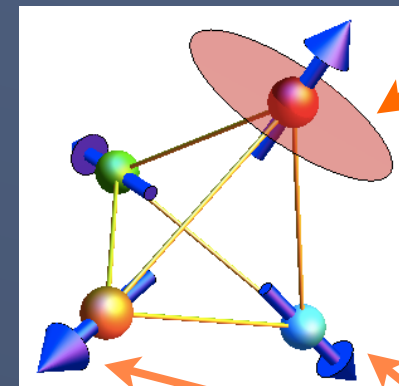
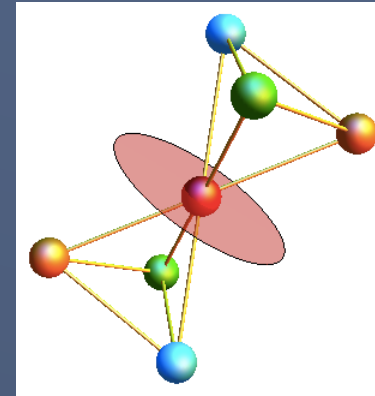
RE ions are heavy - spin orbit coupling is strong

→ anisotropic exchange possible

4 symmetry-allowed terms for exchange tensor

S. Curnoe. Phys. Rev. B 78, 094418 (2008).

see also S. Onoda and Y. Tanaka, Phys. Rev. B 83, 094411 (2011).



*local XY-plane*

*local z-axes*

$$H = \sum_{\langle ij \rangle} \left\{ J_{zz} S_i^z S_j^z - J_{\pm} (S_i^+ S_j^- + S_i^- S_j^+) + J_{++} [\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-] \right. \\ \left. + J_{z\pm} [S_i^z (\zeta_{ij} S_j^+ + \zeta_{ij}^* S_j^-) + i \leftrightarrow j] \right\},$$